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Application of Remote Sensors in Coastal Zone Observations

Jean-Michel Caillat
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PREFACE

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ABSTRACT

A coastal-processes review and biological consideration lead to the determination of the elements which are required in the study of coastal structures and needed for a better use of the ocean's resources. Various remote sensors are analyzed for the information which they can provide and sites are proposed where a general ocean-observation plan could be tested.

I. INTRODUCTION

The purpose of this report is to develop a plan of coastal observations which can be used to provide necessary information for coastal engineering problems. This report will consider the different factors which contribute to a coastal-engineering observation plan, and it will give an explanation of how the final experiment propositions were obtained.

Coastal engineering deals with the conservation, development, and exploitation of the coastline and coastal resources. Its domain of interest is the coastal zone, which is the dynamic boundary separating the sea, land, and air. The realization of a coastal engineering problem requires knowledge of the coastal zone and the offshore zone. It requires the use of wave and weather statistics, wave propagation information, current and tide information, etc.

A review of coastal processes is presented to help the nonspecialist in understanding the problems arising in coastal engineering. For specialists in coastal processes, the material will be somewhat familiar. Then, consideration is given to coastal erosion and coastal structures, noting their economic impact on their surroundings. The next part of this report is devoted to the biology of the ocean, and to the benefits which could be attained by a better knowledge of it.

The subsequent parts of this report are devoted to the sensors which can be used for coastal-zone observations, and the users who would be interested in having information about the ocean conditions. Finally, the report proposes a few sites along the United States coasts where experiments could be conducted in association with governmental or private organizations, to develop methods of study which can be used on a large scale to help solve coastal engineering problems.

II. COASTAL PROCESSES

This section presents an elementary coastal engineering review to help the nonspecialist in understanding the different problems in this area. It will cover wave generation and propagation, wave refraction, diffraction and reflection, and currents.

A. WAVE PROPAGATION AND GENERATION

Ocean waves are characterized by their height, wavelength, and the period from which other characteristic dimensions can be calculated. Figure 1 defines the geometric parameters of an ocean wave. The period of a wave is defined by the time required for two successive crests to pass a fixed point.

Ocean waves cover a very wide range of frequencies. Figure 2 shows a schematic representation of the energy contained in the surface waves of the ocean. It is only an arbitrary representation, but it can be seen that from capillary waves to tidal waves the frequency spectrum extends from 100 cycles per second to less than 10^{-5} cycles per second.

For the propagation and behavior of these waves, with the exception of capillary waves, the small amplitude wave theory, which assumes linearity, is widely used. According to this theory, the equation giving the wave celerity or phase speed is:

$$C^2 = \frac{g}{k} \tanh (kh) \qquad (1)$$

where

- C = wave celerity
- g = acceleration of gravity
- k = wave number with $k = 2\pi/L$
- L = wavelength
- h = water depth

The equation giving the wave length is (Ref. 1):

$$L = \frac{gT^2}{2\pi} \tanh \frac{2\pi h}{L} \qquad (2)$$

with the above notations.

Numerical tables or graphs are used to determine the wavelength. It can be noticed that various quantities (wavelength, height, celerity, etc.) vary as the wave progresses in water of gradually changing depth. The only wave characteristic which does not change with depth is the wave period; therefore, it is a convenient reference parameter.

A classification of waves according to the relative depth h/L is useful. If h/L is smaller than 1/20, then the depth is small in comparison to the wavelength and the waves are called "shallow water" waves (or long waves). The expression for the celerity reduces to:

$$C^2 = gh \text{ (shallow water)}$$

When the ratio h/L is greater than 1/2, the waves are called "deep water" waves (or short waves). Equations (1) and (2) can be written under the form:

$$\left\{ \begin{array}{l} C_0 = \dfrac{g}{2\pi} T \\ \\ L_0 = \dfrac{g}{2\pi} T^2 \end{array} \right\} \text{ for deep water conditions}$$

When the ratio h/L is such that $1/20 < h/L < 1/2$, we are in an "intermediate water depth" case, where the equations cannot be simplified. This classification simplifies the calculation of wavelength and wave velocity for deep and shallow water depths, which are the most frequent cases.

The group velocity, with which the wave energy travels, and the motion of the water particles depend on the water depth. The group velocity C_g varies from 1/2 the wave velocity in deep water to the value of the wave velocity in very shallow water conditions. The group velocity and the wave velocity are related by the following expression:

$$C_g = C \frac{1}{2} \left[1 + \frac{2kh}{\sinh 2kh} \right] .$$

Figure 3 shows the wave-group advance in deep water conditions. As the center of the group advances from A to B, wave number 1 dies out and

wave number 4 forms behind. The orbital motions of the water particles can be represented by the diagrams of Fig. 4.

In shallow water, the water particle motion affects the whole water depth, while in deep water, only the upper layer of water is affected. According to the small amplitude theory, the water particle trajectories are closed, and a given particle should come back to its original position after one period.

Actually, by going to higher order theories (for which the small amplitude theory is the first term), it can be verified that the water particles' orbits are not closed. This allows a slow migration of the particles in the direction of wave travel and creates a wave current. These higher order theories are of particular interest for wave-force calculation in offshore structures.

How waves are generated by wind is another problem and it requires semi-empirical relationships. The problem deals with the growth of waves, and the increase in wave height and period, due to the action of the wind and dependent upon the fetch and the duration. The fetch is the distance over which the wind blows and the duration is the length of time during which the wind blows on the ocean surface. Correspondingly, the minimum fetch (the minimum duration) is that distance (or that duration) required to establish a steady state generation for a particular wind speed and duration (or fetch).

There are a number of theories for deep water wave generation. The two most commonly used are semi-empirical methods: the significant-wave method and the wave-spectrum method. These two methods give fairly accurate estimates of the wave parameters when sufficient calibration data are available. The significant-wave method introduced by Sverdrup and Munk (Ref. 2), also called S-M-B method, describes the sea state by the significant-wave height. The significant-wave height, or $H_{1/3}$, is the mean or average wave height of the highest third of all the waves present in the wave train. It is related to the average wave height $\overline{H}$ as follows: $\overline{H} = 0.625\ H_{1/3}$. The significant-wave period represents the mean period of the significant-wave height. This significant-wave period represents a period around which is concentrated the maximum wave energy.

The wave-spectrum method is due to Pierson, Neumann, and James (Ref. 3) and is also known as the P-N-J method. This method can be used

to predict the spectrum of waves from which the significant-wave height and the statistical distribution of waves can be obtained. A publication of the U.S. Naval Oceanographic Office by Pierson, Neumann, and James provides detailed elements for the understanding and forecasting of the method. Graphs are available (Figure 5 is an example) which give the range of periods to be found in the sea, as well as the energy per frequency band, depending on the wind speed, duration, and fetch.

After their generation, the waves which formed a sea in the storm area travel away and become a swell outside the storm area. The spectrum will change progressively, since the various waves disperse and spread angularly as they leave the generating area. The longitudinal dispersion is due to differences in velocities. A long-period wave will travel faster than a short-period wave and will reach some point earlier. The angular spreading, which is also called lateral dispersion, is due to the fact that the waves were formed by the wind at an angle from the main direction. The amount of energy in each direction can be estimated from diagrams (Ref. 3, Chap. 3). The determination of the direction of propagation of the swell is of great importance in predicting the waves at a given point on the coast, since a slight error at the generating point can mean that the waves will never arrive at the point of forecast. The waves will pass to its side, or will arrive at the point of forecast, but with a different level of energy (different wave height).

Further modifications in wave direction and height will occur when the weather conditions change and finally when the wave trains arrive in shallow water. There, refraction, reflection, and diffraction will take place.

B. WAVE REFRACTION

From Eqs. (1) and (2) we have seen that the phase velocity depends upon the water depth and the wavelength. When the ratio of water depth over wavelength is large, (greater than 1/2), the phase velocity is a function of only the wavelength. This corresponds to deep water conditions. When the ratio of water depth over wavelength is small, (smaller than 1/20), the

phase velocity is a function of only the water depth and we are in shallow water conditions.

For waves, whether linear or not, in water depth small enough as compared to the wavelength ($d/L < 1/2$) (i.e., in shallow and intermediate water depth), each part of a wave travels with a phase velocity which is dependent on the water depth under it. If the water depth varies, the local wave velocities will be different and the wave will bend. This bending is known as wave refraction.

In practical engineering problems, the way waves will refract can be obtained by hand from graphical procedures, or numerically with the help of a computer. Two methods are available to determine these refraction diagrams: the wavefront method and the direct orthogonal method. These two methods do not always result in the same answers. This difference comes from the cumulative errors involved in the techniques used, and, in particular, from the way the irregularities of the bottom topography are treated.

The direct ray or orthogonal method is the most suitable method for obtaining refraction coefficients. The theory for the construction of refraction diagrams by the direct ray method is due to Arthur, Munk, and Isaacs (Ref. 4).

If $n = n(s)$ and $y = y(s)$ (Fig. 6) denote the coordinates of a point on a wave ray in terms of the curvilinear distance s along the ray from some arbitrary point, and if $\theta = \theta(s)$ denotes the angle between the tangent to the ray and the x-axis, the differential equations of the ray are:

$$\frac{dx}{ds} = \cos\theta$$

$$\frac{dy}{ds} = \sin\theta$$

$$\frac{d\theta}{ds} = -\frac{1}{C}\frac{dC}{dn}$$

where $C = C(x, y)$ is a known two-dimensional field of velocity obtained from the wave period and the bottom contours.

These are the equations which form the basis of the graphic method. These equations can also be used for a numerical calculation of the refraction diagrams with a computer, since it can be considered as an Initial Value Problem on the scalar field $C(x, y)$. Several authors have worked on this problem and different solutions have been developed by Yuan Jen (Ref. 4), Goldsmith et al. (Ref. 6).

A problem in the determination of refraction diagrams occurs when two adjacent orthogonals happen to cross each other. Such a convergence, on the basis of the simple theory used here, would indicate that the waves become infinitely high, which, of course, is not the actual case. In nature, the waves tend to peak, then break, and often the result is an agitated ocean surface.

If the problem of refraction can be solved quite easily for a single-period regular wave train (putting aside the problem of crossed orthogonals), it is not as simple with ocean waves which are not regular, but complex. For an actual ocean spectrum, each frequency will be refracted according to its characteristics and produce a result often difficult to forecast. The spectrum in deep water must be determined, and then sliced into frequency bands. The average refraction of each band must be calculated and then the results must be recombined to give the spectrum in shallow water. In parallel to refraction, another problem – diffraction – often comes in the determination of wave paths.

C. WAVE REFLECTION AND DIFFRACTION

Wave reflection occurs when a wave train arrives either on a beach or on a rigid barrier. Part of the wave-train energy is reflected. A vertical barrier, such as a pier or a breakwater, will reflect most of the wave energy, while a small slope beach will only reflect a small portion of the incident energy. Most of this energy is dissipated in the turbulent process of wave breaking. The result of the reflection phenomenon is a wave train traveling in a direction given by a law similar to the optic law of reflection: the angle of reflection is equal to the angle of incidence.

If we remain in the domain of optics, we know that a beam of light passing through a small aperture is diffracted, and, as a result, the diffraction pattern formed on a screen beyond the aperture will show light and dark areas in the region which is geometrically a shadow area. A similar phenomenon occurs when ocean waves arrive at the end of a barrier, as a breakwater, or pass through a gap between two barriers, as a harbor entrance. The Huygens principle explains light diffraction, as well as water-wave diffraction. Each point of an advancing wave front can be considered as the source of a secondary wavelet. A finite length of time later, the resultant shape of the wave front is the envelope of these wavelets. For ocean waves, the case of a barrier end and the case of a gap must be distinguished in the way they are solved.

Penny and Price (Ref. 7), and Putnam and Arthur (Ref. 8) have presented solutions for the diffraction of waves passing a single-arm breakwater. With the help of graphical methods to get numerical values, the theoretical results of Putnam and Arthur can be used to obtain diffraction patterns.

In the case of diffraction of waves passing through a gap, the solution is more complex than for diffraction around the end of a single-arm breakwater. Blue and Johnson (Ref. 9) have considered the problem. Usually graphs or generalized diffraction diagrams are available to determine the diffraction pattern for breakwater design. A separate diagram is required for each different ratio of gap width to wavelength and one must select the proper diagram when constructing wave diffraction. These diagrams give the ratio of local wave height over wave height before diffraction, allowing the determination of the water surface condition at any location.

Refraction and diffraction most often are combined. The bottom seaward and shoreward of a breakwater is usually not flat, and the problem of diffraction is complicated by a refraction problem. A unified theory of the two has not yet been devised. The way to consider such a case is to construct the refraction diagram up to the breakwater, then to construct a diffraction diagram on a distance equivalent to a few wavelengths (4 to 5) and to construct a new refraction diagram to the breaker line. Often a model is used to study cases where shapes are complex.

D. CURRENTS

Another element which affects waves is the existence of currents. Several types of currents exist and may be classified in various ways. Wind-drift currents of relatively short duration, surface wave-induced currents, tidal currents, and major oceanic currents are part of the general circulation. These currents are flows of ocean waters with speeds varying with depth, time, and other parameters, such as water temperature, salinity, etc. Their effect on waves results in refraction when the waves encounter the current at an angle. When the wave direction of propagation is the direction of the current, the waves are flattened; when the current is contrary to the wave direction of propagation, waves become steeper and eventually break on certain conditions. This represents a dissipation of energy in the wave train. Also in that case, short waves can be stopped, because the current has the role of a filter.

Because currents also have a predominant role in mixing processes and in sediment transport, they have to be determined for all types of coastal structures.

III. COASTAL EROSION – COASTAL STRUCTURES

The problems which confront coastal engineers are coastal erosion and the building of coastal structures on the coastline or at some distance from shore. In the following section, we will review these problems, their economic repercussions, and what the coastal engineer needs to know to solve them.

A. ECONOMIC IMPACT OF COASTAL EROSION AND COASTAL STRUCTURES

The coastal zone is the dynamic boundary separating the sea, land, and air. Changes in the dynamic balance between these areas can result in either shoreline erosion or the deposition of sediments on the shoreline. Such coastal erosion frequently results in large losses in valuable property, since the coastal zone is densely populated and the property values are high. Public recreational areas, parks, and beaches which are located along the coast also sustain large economic losses as a result of coastal erosion.

Most coastal erosion results from large waves and tides striking a shoreline of unconsolidated sediments or rock which has been softened by water or fault fracturing. The U.S. Army Engineers Division (Ref. 10) conducted an inventory of the California coastal zone and concluded that 85.8% of the coast contained erosional features that were formed during historical time. They estimate that erosion of potential economic significance is occurring along about 4.4% of the California coast.

Shepard and Grant (Ref. 11) concluded that some portions of the Southern California coast were eroding at a rate of up to a foot a year. There are up to 200 landslides in the 180 miles of sea-cliffed coast in Southern California that have resulted in property damage (Pipkins and Ploessel, Ref. 11). The coast between Dana Point and Palos Verdes includes 38 miles of cliffs, along which 15% has suffered landslides, and more than 90% has undergone some form of mass movement.

Spectacular erosion has occurred at selected locations along the west coast of the United States. The shoreline at "Jumpoff Joe" in Newport, Oregon, has retreated more than 167 feet since 1880 (Byrne, Ref. 13). The resort town of Bayocean, located on the sand spit fronting Tillamook

Bay, Oregon, was completely destroyed and eroded away during the years following the construction of a jetty at the bay mouth. Tinsley (Ref. 14) reported that portions of the coast in San Mateo County, California, are eroding at average rates of up to three feet per year in unconsolidated sediments and softened rocks, and up to twelve feet per year in protected beaches that have been opened to wave attack.

The U.S. Army Engineers Division (Ref. 10) states that erosion of potentially large economic loss could occur along the California Coast at the following locations: Bolinas Cliffs, Lands End, Ocean Beach, Fort Funston, Pacifica, El Granada, Santa Cruz to Capitola, Point Ventura, Palos Verdes, Newport Beach, Dana Point to San Clemente, Oceanside, Sunset Cliffs, Imperial Beach, Crescent City, Fort Ord, and Monterey to Pacific Grove.

Coastal erosion along the western coast of the United States results in large economic losses. An improved coastal-erosion warning system would allow the endangered areas to prepare for the large waves and reduce the potential losses. Figures 7-10 show some cases of problems which were created by erosion.

In the case of structures, a thorough preliminary study has to be made to avoid future difficulties. An example of a problem which developed after completion of a structure is the harbor at Santa Barbara, California. Sand has been obstructing the harbor entrance regularly (Ref. 15, p. 472). As for any other civil engineering realization, a compromise had to be made between the size of the structure (therefore its cost) and the risk of damage (cost of the damage). An error in the risk estimation can be very costly. As another example, the overtopping and subsequent rupture of dams in the Netherlands during the Feb. 1, 1953, storm flooded about 800,000 acres of land with salt water, damaged 47,300 houses, and drowned nearly 1,800 people (Ref. 16). The same kind of risk factor applies to a power plant located on the shore. The safety conditions will be determined by the knowledge of the probability of a given storm or of given waves. As onshore and offshore power plants are to become more numerous, the problem is of importance for safety and economic reasons. In a general sense, the knowledge of coastal phenomena needs to be improved to protect people

and their property, since the coastal zone is usually a most densely populated area.

B. COASTAL EROSION

Sediment transport, including erosion and sedimentation, is due to wave action on the ocean bottom. From the previous discussion, we saw that in shallow or intermediate water depths, the orbital motion of water particles exists across the whole water depth. The water motion so created on the ocean floor is powerful enough to generate motion of sand particles. As finite height waves result in a wave current the particles will move, and in areas where waves lose their energy these particles will be deposited.

A very important part of sediment transport occurs where the breaker lines are located. When the waves arrive at an angle to the beach, a longshore current results in the surf zone. This longshore current is often able to carry a large amount of sand. The larger the wave height, the deeper the water depth is at the breaker zone and the power of the wave crest becomes greater. Thus, larger sediments can be transported, and they will be moved offshore into deeper water and cause coastal erosion. The greater amount of erosion will occur when large waves correspond with the spring tides and the wave power is impacted high up on the shoreline.

C. COASTAL STRUCTURES

1. Breakwaters and Jetties

Breakwaters and jetties are the basic coastal structures used in civil engineering. The function of jetties is to protect a navigation channel from sediment movements to maintain a project depth. They also often act as breakwaters whose purpose is to reduce the wave heights in their lee; therefore, we will consider breakwaters and jetties at the same time.

Rubble-mound breakwaters are made of a core of quarry run which is covered by layers of larger stones for stability. The formula commonly used in engineering to determine the stable slope α is the following formula, which was established by Hudson (Ref. 17) and calibrated by the U.S. Army Corps of Engineers Waterways Experiment Station (Ref. 18):

$$W = \frac{\gamma_r H^3}{K(s_r - 1)^3 \cot \alpha}$$

where W is the rock height in tons, γ_r is the specific gravity of the stone ($\approx$150 lb/ft^3), H is the wave height in feet, s_r is the ratio of specific gravity of the stone to water, and K is a coefficient which depends on the type of material used on the upper layer. K increases from 2.0 for rounded pell-mell stone to 8.0 for sharp fitted stones. Concrete blocks of various shapes (tetrapops, tribars, dolosse, etc.) are used when no large rocks are available.

The size of the rocks to be used and the design height of the breakwater are obtained when the water level and the maximum wave height, which can be expected at the location, are determined. Economic considerations will determine the optimum height of the breakwater when the amount of damage which would occur if the waves partially overtop or destroy the breakwater is compared to the cost of building a stronger and higher breakwater. Tide and wave-height statistics are necessary to get these parameters. It is also necessary to have an indication on the wave directions and their frequency of occurrence to determine the orientation to give to the breakwaters for the best possible protection.

2. Harbors

Harbors generally require very expensive coastal engineering works; therefore, they must be studied carefully. Harbors are used for protection, loading, and unloading of vessels. They are usually located close to a city from which the ground support (labor, communications, etc.) is available. Coastal engineering works in the creation of a harbor consist of the construction of piers where vessels are moored, and of breakwaters and jetties to provide access and protection from the outer ocean.

The piers must be dimensioned so that they resist the efforts created by the moored vessels and the wave action. The breakwaters and jetties must be dimensioned as explained in the previous paragraph. Their location

must be carefully determined to reduce wave heights inside the harbor by taking advantage of refraction and diffraction. Their position is also of importance because of the resonance phenomenon which occurs when the frequency of the incoming waves corresponds to the frequency of the resonator formed by the harbors' basins. This phenomenon can rupture even very strong mooring lines.

The creation of a harbor also requires knowledge of the bottom topography, not only in the harbor itself, but also far outside of the harbor to determine the refraction patterns and to position the harbor entrance where it is most likely to have lower wave heights at all times. Obviously, wave statistics are necessary for such a study.

3. Offshore Moorings

Offshore moorings became a necessity to provide shelters of adequate depth for oil tankers or for bulk ore carriers of ever increasing size. The requirements for the location of a deep water mooring are that the tankers can be maneuvered towards the mooring, remain moored to it, and vacate it, all in a safe manner. The location is usually a compromise between the maneuvering clearance and the cost of the mooring point, considering higher costs for greater water depths and longer pipelines.

The creation of an offshore mooring requires the knowledge of several elements. The water level must be known to determine the underkeel clearance of the tanker and the position of the buoy (or buoys) to which the tanker moors. The water level is determined from mean sea level, adding the effect of tides. It is necessary to know high highwater and low lowwater levels. The effect of storms (storm surges) and of meteorological tides on the water level must also be estimated. The current must be estimated in velocity, direction (at different depths), and pattern. The winds must also be estimated in strength, direction, and duration. Winds have a great influence on tankers, which present a large cross-section to them, and on the water surface, where they can create important local waves.

Waves have the greatest effect on the operation of an offshore mooring, and wave statistics are necessary to determine the occurrence and duration of the wave heights limiting the operation. The wavelength, the wave period, and the wave height must be known to estimate the mooring forces, as well as the wave direction.

Meteorological elements are also required. Visibility can be reduced in fog and heavy rain, and this creates delays and further operating limitations. Low temperatures and ice may cause difficulties with the pumping of oil and the stability of the buoy. They must, therefore, be investigated.

Other necessary parameters to be considered are the soil and bottom conditions. The bottom contour lines must be established with precision to locate the safe areas where the vessel can maneuver. The quality of the soil determines the anchoring system of the buoy.

Numerous parameters must be taken into account to determine the location of a deep water harbor. The choice depends, as for other structures, on a balance between engineering capabilities and economical reasons determined by the local conditions.

4. Drilling Platforms

Offshore platforms are used as fixed bases from which oil drilling or mining operations are conducted. A glance at a world map of potential offshore oil production areas shows the important future need for this kind of structure. Many types of platforms exist, but they all have the same purpose: to provide a stable base so the drilling pipes will not bend excessively during the operations, and to provide safety with respect to the waves. To meet this last requirement an offshore platform must be designed high enough to be above the combination of the highest waves on top of the highest astronomical and meteorological tide. The effect of refraction must be considered to avoid locating the platforms where refraction builds up waves, and creates unnecessary hazard.

The study of a drilling platform site will, therefore, require a study of wave statistics, of local bottom topography for refraction purposes, of local geology, and of currents (from waves or others) which could create scouring around the platform.

5. Floating Structures

Floating structures include vessels, buoys, nets, floating dredges, floating platforms, etc. The primary function for a floating structure varies from maintaining the structure at a particular location to performing a given task. The factors limiting the operations of a floating structure are excessively high waves, poor visibility, currents, or other factors, such as human factors, which can be of importance.

A new type of floating structure which is expected to be developed in the near future is the floating power plant. As coastal power plants, these facilities (nuclear or conventional) would have a large amount of cold sea water which they could use for cooling, and they could be located within a short distance from users (industry, urban areas, etc.). An oil-burning power plant could be anchored in some sheltered area along the coast and could provide an unloading facility for tankers. Building such a structure would require a geologic survey of the area to estimate the anchoring capabilities of the soil, knowledge of wave statistics, and determination of refraction diagrams, as well as the pattern of the currents. In this case all these elements would have to be known with precision to make an estimate of the safety coefficient.

Power plants are one kind of envisionable large floating structure, but other large structures such as refineries or plants could also be installed on a floating base as well.

D. ELEMENTS USED IN COASTAL ENGINEERING

Although we have not reviewed all types of coastal structures, it can be seen that their design and construction always require the same group of elements. These are physical elements, geological characteristics of the soil and its condition, wave statistics, refraction diagrams, weather statistics, currents, tides, and storm surges. In addition there are also nonphysical elements, such as sociological and economic requirements, aesthetics, ecology, and politics, which must be considered in planning coastal structures.

The following section will describe how the physical elements, mainly the ocean related elements, are obtained so that they can be used in the design of coastal structures.

1. Wave Climate and Wind Climate

In all design of coastal structures, the main elements which are needed are the probability of a given wave period and wave height coming from a given direction, and the probability of a wind with a given speed and duration. Usually records are available for the wind conditions in most locations (from measurements or estimations from weather charts); however, wave records are not as complete. Records of waves only exist for specific points along the coast, and usually they consist of visual estimates of the wave height and direction. These visual estimates imply errors, or at least inaccuracy. Furthermore, the waves observed near shore are different from the water waves in the open ocean. Good wave records for the open ocean do not exist and still remain to be established for use in coastal engineering.

2. Wave Refraction

The knowledge of wave refraction patterns obtained from mathematical models or from observation allows us to determine the energy distribution along the coast, i.e., to determine the height and the direction of the waves arriving to shore from a deep-water wave train. As explained in the chapter on coastal processes, mathematical models can provide a wave refraction diagram from the bottom contours, the wave period, and the wave direction. To obtain good results, they usually are time consuming and expensive to run. Refraction diagrams from observation take even longer to obtain, since one observation will only yield the refraction pattern for one period and one direction. The most useful and efficient method to be used is often a scale model for which any condition can be created.

3. Currents

The characteristics of the currents in a location are important to know. In the case of an outfall, the current will determine in which

direction(s) and at what rate the effluent will be dispersed. In the case of an offshore mooring, the current will determine the position of a vessel and the efforts in the mooring lines. Also the knowledge of currents contributes to the estimation of the amount of sediment transport.

Two methods exist to represent currents. One is the Lagrange method or "path method." It follows the behavior of a given fluid particle during its motion through space. The other method is the "flow" method of Euler. Euler's method observes the flow characteristics in the vicinity of a given point as the particles pass. Current speeds and directions must usually be obtained from surface sensors.

Subsurface sensors also have to be used since the characteristics of a current vary with depth. The sensors can be buoys, drifting floats, dyes, current meters, etc. The type of instrument used depends on whether a "flow" or a "path" pattern is desired, and on what type of current is to be measured.

4. Tides

The quantitative prediction of tidal variations for a given location cannot be made by considering only the tide producing forces. The tidal-wave speed depends on the water depth. There are reflections, frictions, amplifications, and attenuations due to submarine features or shoreline. A tide prediction at a particular location requires the analysis of tidal measurements at that location conducted over a long period of time. Storms and particular meteorological conditions must be eliminated in order to keep adequate records for analysis. From these records the amplitude and phase of the tidal constituents at a given locality are determined and future tidal variations at that locality can be predicted.

The water level variations are usually obtained from an apparatus such as the one depicted on Fig. 11. The circular pipe is closed under the water except for a small orifice. Long-period variations (tidal variations) are transmitted while shorter-period variations (wind waves) are damped. The variations of the position of the float are recorded on a drum. The recording is then analyzed to get the tidal components from which tide forecastings can be made.

5. Storm Surges

A storm surge occurs when winds are blowing towards shore and are creating a rise of the water level because of the wind stress on the ocean surface. To solve the problem several cases must be distinguished depending on the type of water body (lake, coastline, offcoast, estuaries, etc.) and on its geometry (rectangular, regular in shape, very irregular in shape). For each case a theory has been associated and gives the expected water-level rise for a given wind speed, fetch, and duration.

These methods are calibrated for a given location with the values obtained from previous storms (tide measurements compensated for meteorological tide). When storm surges have been predicted fairly accurately in the past, by one method, the same method is usually applied for some future design storm. This requires that tide components are known (therefore that tide measurements exist) where the structure is to be located in order to estimate the height of the total tide during storms.

E. SUMMARY

Sediment transport and coastal erosion are problems of large economic impact. The construction of coastal structures also requires important investments. Sediment transport, coastal erosion, and coastal structures have the same group of necessary parameters as wave and weather climate, wave refraction, currents, etc. How well these parameters are known and how easy it is to obtain them can improve coastal engineering results.

Table 1. Parameters necessary in physical oceanography

Structure or phenomenon	Wave-height statistics	Wave-period statistics	Wave-direction statistics	Currents	Bottom topography and soil	Wind direction and velocity statistics	Tides	Storm surges
Sediment transport	X	X	X	X	X			X
Breakwater design and harbor	X	X	X		X		X	X
Offshore moorings	X	X	X	X	X	X	X	X
Floating structures	X	X		X	X	X	X	
Deep-water wave forecast	X	X	X			X		
Shallow-water wave forecast	X	X	X		X	X	X	X

IV. BIOLOGICAL CONSIDERATIONS

The coastal zone is among the most biologically productive of natural ecosystems. This is largely due to its physical structure; it forms a tripart interface between the liquid, solid, and gaseous phases of the planet. Interfaces tend to chemically and physically concentrate materials; the biota exploit this concentration. Many examples can be drawn of these concentrations and exploitations:

1. Tidal marshes. Such marshes are built on fine silt deposited when salt and fresh water meet in estuaries. The fine silts form enormous surface areas between liquid and solid phases trapping by adsorption the mineral elements essential to plant growth. Continuous or near-continuous inundation provides ample water. Emergent plant productivity is thus greatly enhanced.

2. Estuaries. These form the interface between fresh and salt water systems. Silt precipitation forms deposits supporting vegetation (as above) as well as habitat for many animals which feed on the detritus from marshes and other fractions of the estuarine production and decomposition cycles. The peculiarities of estuaries make many a nearly closed, recycling system; hence, the materials necessary to high biological productivity are concentrated. Unfortunately, this characteristic also leads to concentration of man's wastes for which estuaries are favorite dumping grounds.

3. Nearshore upwelling. The coastline as a finite boundary to the ocean often produces fluid dynamic consequences which lead to upwelling of deep, nutrient rich water into the coastal environment, greatly enhancing biological productivity.

These and other biological and physiochemical properties of the coastal zone make this dynamic area extremely important to man. This importance is at least partly reflected in the following statistic. Presently in the United States, 30% of the population lives along the coastal regions which represent

only 8% of the total land area in this country, and this trend is increasing. The possibilities and examples of misuse are thus nearly infinite. Rational management leading towards multiple use with minimum long-term negative consequences demands an active, multifaceted monitoring program which adequately addresses both the critical parameters and critical management issues. This report will outline one approach to such monitoring by utilizing remote platform sensors integrated with conventional data sources. It is organized along an issue or ecosystem component approach, and focuses principally on the general areas of coastal fisheries and estuarine ecosystems.

A. COASTAL FISHERIES

At issue here are both the question of assessment of stock availability and the enforcement of quotas arrived at from that assessment. These fisheries are best viewed from a habitat perspective. Primarily, they are either benthic (bottom dwelling) or pelagic (near-surface dwelling). Although fishing techniques would obviously differ for each, current management techniques do not. Coastal United States fisheries, with the exception of some of those which overlap into international waters and are internationally exploited, are not subject to management. Many, if not all, however, could and should be managed for long-term sustained productivity. Several management schemes have been proposed, and at least one utilizes information derived from remote measurement of physical properties of the environment. These measurements are utilized to derive biological simulation models which output management information. Regardless of the scheme proposed, however, two requirements remain paramount. First, institutional (i.e., governmental) constraints must exist to set priorities for management strategy; and secondly, a means must be found to enforce any given strategy.

A third and often overlooked factor of particular importance in the coastal zone is the importance of sport-fishing activities, since these activities impact resources subject to commercial exploitation and sport fishermen may comprise a politically more potent force than commercial fishing interests. Any scheme suggesting management of coastal fisheries must account for the impact of sport-fishing activities. The possible

role of remote sensing systems in the area of fisheries management, both sport and commercial, will be treated in the Sensor/Mission section.

B. ESTUARIES AND TIDAL MARSHES

The potential productivity of these ecosystems has been briefly outlined in the introductory remarks. The principal issue facing these fragile but indispensable systems is reconciling the multiple demands made by an affluent society with the importance of these systems to the biosphere. The biological impact of estuaries and tidal marshes goes far beyond their limited geographical extent. In addition to their contained productivity, their exported productivity is at the center of nearly all coastal fisheries. With few exceptions, all species of fish of commercial or sport interest in the coastal zone are dependent at some point in their life cycle on the enormously productive coastal estuaries and marshes. The marshes and estuaries further form the habitat exploited by such varied migratory species as ducks, geese and other waterfowl, salmon, shad and other anadromous fishes (often exploited far inland of the conventional coastal zone), and many marine mammal species.

The underlying management issue with respect to estuaries and marshes deals with their unfortunate suitability as industrial and residential sites. They offer broad, flat expanses, access to water, and a convenient dump for waste materials. Recognizing this desirability and its effects on the natural role of estuaries, many coastal states are enacting or have enacted strict land-use statutes for coastal areas. Nonetheless, enforcement of these statutes, as well as monitoring of the effects of existing developments, remains a formidable task. The use of remote systems offers many virtues to be treated in the Sensor/Mission section.

C. MISSION/SENSOR SPECIFICATIONS

This section will expand on the previous section and will be organized around specific management issues. For each of these management issues a suggested mission approach will be given as well as a discussion of appropriate sensor systems and their role as data sources. A few general remarks, which apply to the data demands of coastal-zone management,

are in order. Many of the physical characteristics of the coastal zone are driven by tidal influences. Consequently, many of the most significant of the biological manifestations of this zone are also tidally linked. Principal among this group are the effects on the biota of tidal currents and inundations, which occur with (on the average) 6-hour inflections. This periodicity thus sets the upper limits for coastal-zone surveillance missions. One immediate consequence, without considering the other resolution limitations on remote sensors, is that satellites as sensor platforms become severely constrained. Two possible modes for use of satellites (geostationary or with ΔV capability) can be considered, but each has severe drawbacks. In the case of a geostationary vehicle, spatial-resolution requirements probably cannot be met. Conversely, mission length would require too large a propellant payload commitment in a vehicle with ΔV capability. Thus, principal attention in this section will be given to aircraft missions and systems. The following, then, are the critical biological and chemical considerations for coastal-zone management and the suggested reconnaissance roles for NASA aircraft programs.

1. Regulation of Coastal Fisheries

Regulation of coastal fisheries entails two separate issues. On the one hand, adequate forecasts of available resources must be made so that these may be apportioned among the various (national and multinational) fishing interests. Secondly, a means must be found to enforce derived quotas and their apportionment. Direct assessment of fishery stocks, even given the spatial resolution possible from aircraft altitudes, is unlikely for most of the important coastal fisheries. Rather, sensor systems could be utilized to monitor critical environmental parameters which will be utilized as inputs to simulation models for the fisheries. From such models will come spatially and temporarily coherent estimates of harvestable resources for all the major coastal stocks. In this fashion both surface and demersal (bottom) fisheries can be addressed by remote sensor data. In the latter case (demersal fishers), measurements of surface conditions by remote

sensors will relate to juvenile stages and potential recruitment to adult populations (most benthic species have surface-living larval or juvenile stages). In the case of surface species, all stages of the life cycle can be related to and modeled from surface environmental measurements. Of particular interest for the yield assessment models will be data on such environmental variables as temperature, salinity, nutrients, and plankton production. Behavioral models, which relate such activity as feeding preferences to environmental features, may be useful for real-time fishing decisions. Similar data will drive these behavioral models, as well as information on thermal or color (tidal) fronts and other interfacial information.

Once assessment has been achieved and realistic predictions produced and allocated, surveillance for enforcement will require that type, position, and condition of all fishing vessels be known. Two approaches for this are possible: 1) a black box on each vessel which automatically encodes and broadcasts such data; or 2) an active surveillance instrument (radar) in cooperation with random surface-surveillance methods.

Input requirements for stock assessment models will likely be the least temporally demanding. Fishery decision models will require at least daily if not more frequent input (near-shore fisheries will likely require at least semitidal input). For those fisheries operating in upwelling environments, sensor systems such as passive and active microwave systems, which have the virtue of near all-weather operation, can be utilized to monitor the dynamic processes occurring during upwelling, thereby providing the necessary inputs to management models. Specifically, a microwave scatterometer capable of sea-surface wind measurement can be used to monitor wind-driven upwelling. Passive radiometers may ultimately provide distributional data on temperature and salinity for use both in management and decision modeling.

For surface fisheries such as albacore or menhaden, where color/turbidity front locations are important to fishing decisions, data of necessity will come only from visible imaging instrumentation. Here, aircraft are indispensable. Under many cloud-cover conditions which would preclude

satellite observation, aircraft could operate below the clouds to continue to acquire valuable data for fishing decisions. Surveillance activities for enforcement purposes should occur at least twice daily, during daylight and at night to oversee operations on both day and night fisheries.

2. Coastal Marshes Management

Management of coastal marshes requires data inputs which address the viability of the marsh. Thus, they basically relate to man's impact on these marshes. Such impacts include dredging and filling for various development activities, alteration of flow regimes which change inundation patterns, and manipulations of the sediment flow patterns which alter the steady-state substrate composition. The first indications that any of these activities are adversely affecting marshes appear as a change in vigor in the plant population which is easily identifiable as changed in the visible/solar IR reflectance spectrum. Thus, scanner or photographic imagery in these wavelengths acquired at weekly or shorter (illegal dredge and fill can ruin a marsh in a matter of hours) intervals can successfully monitor marsh ecosystems.

3. Monitoring General Estuarine Conditions

Use of visible and thermal band imagery is ideal for routine monitoring of tidal and storm circulation in estuaries. Acquired at subtidal time intervals, a history of normal patterns accrues which can be extremely useful in controlling random events such as spills of hazardous substances. Such data is also useful for predicting dispersement and impact areas of low-level, constant contaminants such as cultural/industrial waste. Highly productive tidal flatlands can be monitored with the same imagery for changes in dimension or inundation patterns which may adversely affect shellfish production.

4. Management and Inventory of Migratory Species

The high productivity of estuarine areas is exploited by numerous migratory species in addition to those species which spend their entire life

cycle in an estuarine environment. Examples of periodic visitors include waterfowl, small whales and dolphins, and large fish, such as tarpon. In many cases (for example, waterfowl), the presence of these species and some idea of their impact can be gained from visible wavelength imagery. This same imagery can be utilized in stock assessment of the migratory species themselves. Tables 2-5 summarize the management issues as presented, including remotely observable phenomena, recommended observation frequency, and applicable systems. A summary of the sensors needed in each of the above applications can be found in Tables 2-5. For the following tables, the listed sensors correspond to these definitions:

IMAGING RADAR - Side looking, synthetic aperture; state-of-the-art resolution

THERMAL SCANNER - 8-14 μm; 1.0°C thermal resolution; 1-3 nrad spatial resolution

VISIBLE SCANNER - Multi-channel line scanner; 25-50 nm band width; 0.5 nrad resolution

MICROWAVE SCATTEROMETER - Parallel to SEASAT instrument

VISIBLE SPECTROMETER - Visible band, nadir pointing

MICROWAVE RADIOMETER - Multi-frequency (SEASAT equivalent)

INFRARED RADIOMETER - 8-14 μm, nadir pointing 0.1° C resolution

Table 2. Fishery management sensors

Observation		Imaging radar	Radiometer		Scanner		Microwave scatterometer	Visible spectrometer
Phenomenon	Frequency, h		Microwave	Infrared	Thermal	Visible		
Temperature (pattern)	12h		X	X				
Salinity (pattern)	12h		X					
Thermal fronts	6h	X	X	X				
Color fronts	6h					X		X
Upwelling[a]	12h	X		X	X	X	X	
Currents	6h	?		?	X	X		?
Fishing[b] vessels		X			X	X		

[a]Scatterometer for dynamics and others for confirmation.

[b]As a part of the enforcement procedure.

Table 3. Estuarine conditions sensors

Observation		Imaging radar	Radiometer		Scanner		Microwave scatterometer	Visible spectrometer
Phenomenon	Frequency, h		Microwave	Infrared	Thermal	Visible		
Tidal circulation	6h	?			X	X		
Waste disposal	6h	?		X	X	X		
Tidal flatlands	6h	X			X	X		
Concentration sites[a]	daily				X	X		

[a]Assumes long-term surveillance. Includes eutrophication, thermal entrapment, possibly chemical entrapment if observable through secondary effects. Requires data base against which comparisons (change detection) are undertaken.

Table 4. Coastal marsh sensors

Observation		Imaging radar	Radiometer		Scanner		Microwave scatterometer	Visible spectrometer
Phenomenon	Frequency, h		Microwave	Infrared	Thermal	Visible		
Specification	Semi-yearly					X		?
Vegetative vigor	Weekly					X		?
Illicit dredging, etc.[a]	See comments					X		

[a]Observation frequency depends on potential threat in areas of known violation. Constant surveillance may be required.

Table 5. Migratory species sensors

Observation		Imaging radar	Radiometer		Scanner		Microwave scatterometer	Visible spectrometer
Phenomenon	Frequency, h		Microwave	Infrared	Thermal	Visible		
Population survey[a]	Daily - weekly					X		
Impact	Weekly					X		

[a]Particularly for waterfowl which are visible against background and less useful for marine species.

V. SENSORS

This chapter will review the different sensors which are available to obtain data about the ocean surface and the coastal area. A few remote sensors will be discussed in some detail while classical surface sensors will only be briefly mentioned. Among the remote sensor category, we will look at the imaging radar, the radar and laser profilometer, the scatterometer, and photography.

A. COHERENT IMAGING RADAR PRINCIPLE

Basically, a synthetic-aperture imaging radar consists of a coherent radar on a platform moving with a uniform velocity, whose antenna becomes a new element of a synthetic-antenna array with each successive transmission. The transfer functions of the radar subsystems are linear and such that the amplitude and the phase of the returned echo is preserved. Coherent processing of the successive echoes can, therefore, be carried out in a data-processing system which can reconstruct the original scene and generate high resolution imagery (see Fig. 12). The basic approach is similar to the one used in holography. The attractive feature in the coherent radar system is that an exact replica, amplitude and phase, of the reflected echo is recorded and transmitted to the processing center where large computers are available. The mission can then be "reflown" many times to focus on some specific parameters.

The coherent-imaging radar provides its own illumination and can see through heavy cloud cover; therefore, it can be considered as an all-time remote sensor. The imaging radar "sees" the ocean surface with microwave "eyes"; therefore, it generates information which can best be "seen" in that region of the electromagnetic spectrum. On the other hand, by using the synthetic aperture technique, very high resolution (a few tens of meters) accuracy can be obtained with relatively small antennas.

The synthetic aperture radar technique is a well-tested technique for surface imaging from airborne and spacecraft-borne platforms. The first airborne imaging-radar systems were developed in the 1950's and

were used for military purposes. Their commercial and scientific use became apparent in the mid-60's, and many industrial companies and research laboratories carried on extensive development and research work on the unique capabilities of this new instrument. Some of the first and most known organizations associated with the use of the airborne imaging radar for scientific and commercial purposes are the University of Michigan (military, geology, environment), the University of Kansas (agriculture, geology), Goodyear (geologic mapping in Brazil, Venezuela, and Indonesia), and the Jet Propulsion Laboratory (geology, polar-ice study, oceanography, system analysis for spaceborne missions).

On the other hand, airborne radar imaging of the ocean surface was, and still is, carried out by the Jet Propulsion Laboratory team, and the imagery obtained has generated large interest in the scientific community (see Figs. 13 and 14) for its application in the study of ocean dynamics and surface-wave spectra. Ocean imagery was obtained during a number of missions (Alaska coast, 1971; California coast, 1971; Florida coast; Gulf of Mexico; and Pacific Ocean south of Acapulco, 1973).

To the author's best knowledge, ocean-wave imagery was first obtained with the L-band JPL imaging radar. This band of the spectrum seems very adequate for ocean imagery, but in the near future the JPL radar group will carry an airborne imaging-radar mission simultaneously at 200 cm, 25 cm and 3 cm. This test should relate surface phenomena to the radar frequencies and assist in selecting frequencies for future operational ocean-imaging radar systems.

Currently, we know of a limitation for observing waves with coherent radar. This limitation is inherent to the motion of the waves on the ocean surface. The radar imagery is not taken as a snapshot, but is the correlation result of a continuous flow of data, and usually it takes 1 to 10 seconds of data collection (called aperture formation time) to generate an image of a specific area. High surface resolution requires a long aperture formation time. This, in turn, implies that the wave pattern moves a longer distance, which might lead to a blurring of the periodic pattern; therefore, there is a limitation on the shortest surface wavelength that could be imaged. A nominal value is about 10 to 15 meters. Special processing and pattern

recognition techniques can be used to sharpen the imagery, but such a process requires special purpose computers.

B. RADAR AND LASER WAVE PROFILOMETER

The laser profilometer provides a direct measurement of the surface topography along the line of flight. The ranging technique consists of amplitude-modulating a continuous wave laser. The reflected light is usually collected by a Schmidt-Cassegrain telescope, detected by a photomultiplier, amplified, and phase-compared with the modulation frequency of the transmitted beam. The phase difference between these two signals is proportional to the transit time of the light, hence, the range to the illuminated spot straight under the aircraft. The change in the range to the surface provides the relative surface profile, i.e., the wave profile. Evidently the vertical motion of the aircraft has to be taken into account.

Since the aircraft is a moving reference, it is necessary to convert the observed wave spectrum to fixed coordinates. The conversion technique used involved accounting for the speed of the aircraft relative to the phase speed of each wave-frequency component. Usually it is assumed that all waves are traveling in the direction of the wind. The presence of swells would then lead to errors if the direction of the swells is not known. This is also a limitation on the capability of the laser profilometer in providing the swell spectrum. The laser provides a line profile along the line of flight. This gives the swell spectrum only if the line is parallel to the wave direction; otherwise, two-dimensional imagery (radar or photo) is needed.

Another source of error is that of the aircraft motions: heave, pitch, and yaw; however, the majority of range errors are associated with aircraft motions in the very low-frequency band of the spectrum. As a result, the most convenient technique for removing these errors is simply high-pass filtering, where the low-frequency cutoff selected depends upon the turbulence and, for most cases, is less than that associated with a true wave frequency of 0.07 Hz. Finally it should be pointed out that for presently available laser profilometers, the aircraft has to fly at altitudes of a few hundred meters due to the limitation in the laser power.

Surface profiles can also be determined with a radar profilometer (altimeter). The major requirement is that the spot size on the surface is smaller by at least a factor of two than the smallest wavelength to be measured. This immediately implies that this system is most useful for deriving the line spectrum of relatively large gravity waves. A simple relation between the radar parameters (altitude H, antenna size L, wavelength λ) and the ocean-wave wavelength Λ is:

$$\Lambda > 2 \frac{\lambda H}{L}$$

To illustrate, for $\lambda = 3$ cm, $L = 3$ m, $H = 1000$ m, then $\Lambda > 20$ meters.

C. SCATTEROMETER

The scatterometer determines the radar backscattering cross-section of a certain area as a function of the local incidence angle. This cross-section could then be used to determine the small scale surface roughness, slope distribution, and scatterer size. Finally the surface roughness is used to derive the local wind. There are two basic techniques for backscattering function measurement: 1) the side-looking technique and 2) the Doppler technique.

1. Side-Looking Scatterometry

The geometrical arrangement for side-looking scatterometry is shown in Fig. 15. A short pulse (or chirp pulse) is transmitted toward the surface and the returned echo is sampled and recorded. Each successive sample in the echo corresponds to a different time delay and, therefore, a different surface-incidence angle. Thus, the backscattering cross section as a function of the incidence angle can be inferred from the amplitude measurement throughout the echo as a function of the time delay.

One major drawback for the use of this technique is the fact that different incidence angles correspond to different locations on the surface. Therefore, for a specific area, the scatterometer measures the backscattering cross-section only at one incidence angle. Only in the case where the surface roughness is constant would the system provide a complete

backscattering function. The advantage of this technique is that the radar covers a very wide swath to the side of the moving platform.

2. Doppler Scatterometry

The geometrical arrangement for Doppler scatterometry is shown in Fig. 16. The echo's component scattered from a surface region ahead of the aircraft is positively Doppler shifted, while the one scattered from a region behind the aircraft is negatively Doppler shifted. Therefore, an analysis of the echo's amplitude as a function of the Doppler shift would allow the determination of the backscattering cross-section for a certain region. As the aircraft moves, the local incidence angle at a specific region changes, and an adequate processing of the data would allow the generation of the backscattering function for each specific region.

The Doppler scatterometer measures the roughness over a narrow swath below the aircraft, but on the other hand, it provides the complete backscattering function for each point. It therefore provides a more accurate evaluation of the surface roughness than the side-looking scatterometer.

3. Oceanographic Application

Local wind interacts with the ocean surface and generates capillary waves. The resulting roughness could then be measured with a scatterometer. Many models were proposed to relate the local wind speed to the backscattering function, and field measurements were carried out by the Naval Research Laboratory using a multifrequency scatterometer. From the experimental results, it seems that the X-band region scattering is the most sensitive to the wind speed; therefore, it is the best operating region for an oceanography scatterometer. This could be easily explained by the fact that capillary waves have dimensions of a few centimeters and therefore would interact most efficiently with electro-magnetic waves of the same dimension.

D. PHOTOGRAPHY

Photography, especially aerial photography, has been used for a long time and is a very useful tool in the study of ocean surface and coastal processes. A photograph is usually easy to interpret since what the camera sees is similar to what the human eye can see and a high resolution can be obtained with the use of very fine grain films. The camera can be looking straight down or at an angle with respect to the vertical, but in any case the correction of the image is a simple geometric problem. If a particular phenomenon is to be observed, a film sensitive to a corresponding band of the light spectrum can be used, or various filters can be mounted on the camera. These techniques allow the study of sediment transport, currents, water temperature variations, etc.

The weak point in the use of photography is that clouds prevent the camera from seeing the ocean surface or the ground. This can be a handicap if a mission is scheduled to be flown on a given day and the weather happens to be cloudy. It should also be mentioned that the strongest waves usually occur during overcast periods.

E. SURFACE SENSORS

Surface sensors are required when long-duration measurements have to be done or when a remote sensor cannot provide the desired measurement. These sensors can measure wave height, wave period, water temperature, wind direction and intensity, currents, etc. They can be buoys with an inertia system which transmits by radio the wave-height variations, pressure gauges which give the same information by detecting the pressure variations due to the wave on the ocean floor, thermometers, air humidity detectors, or anemometers. A very wide variety of instruments exists and they are described in oceanographic journals. Surface sensors need to be used during the experimental stages to verify remote sensor measurements.

Table 6. Sensor applications

Parameters	Imaging radar	Scatterometer	Laser profilometer	Scanner		Radiometer		Photography	Surface buoys	Bottom sensors
				Thermal	Visible	Microwave	Infrared			
Wave height			X						X	X
Wave period	(in deep water)		X					(in deep water)	X	X
Wave length	X							X	X	X
Wave direction	X							X		
Currents	?			X	X		?	X		
Water depth										X
Wind direction									X	
Wind velocity		X							X	
Water temperature						X	X			
Salinity						X				
Thermal fronts	X					X	X			
Color fronts					X			X		
Upwetting	X	X		X	X		X	X		
Fishing vessels	X			X	X			X		

VI. POTENTIAL USES AND USERS OF COASTAL OBSERVATIONS

Potential users of ocean and coastal observations exist in many branches of government agencies and in private industry. The following is a list of potential uses and users of a coastal observation and forecasting program:

- The U.S. Army Corps of Engineers and private consulting and building firms could use the data as input for the determination of coastal engineering works characteristics.
- ERDA (Energy Research and Development Administration) could use the data for planning offshore and onshore nuclear and conventional power plants.
- NOAA (National Oceanographic and Atmospheric Agency) could gather wave climate and weather climate information as well as near coast currents for the U. S. Coast.
- NMC (National Meteorological Center) could use the data for the prediction of wind-generated waves and swells, and for forecasts of wave heights.
- Offshore oil operations would use this information to plan their work schedules.
- Coast Guard and Harbor Patrol offices could use the wave and surf conditions forecasts to post warnings for ships and boats.
- Lifeguard stations could use the surf and longshore current predictions.
- Highway departments could use the erosion predictions to try to protect endangered roads or to plan new roads in the coastal vicinity.
- Local government could use the system to protect property that could erode away in short, medium, or long terms.
- Department of Parks and Recreation could use it for beach management.

- Harbor authorities and ship masters could use the wave and swell forecast for mooring of vessels.
- Fishing boat fleets could locate the best fishing spots.
- Water pollution agencies could survey the ocean water's quality.
- A chart showing the position of ships and boats could eventually be obtained at regular time intervals.
- Navigation companies could use the observations for the choice of the best route for their ships.

This list can certainly be extended since the monitoring of wind and wave conditions is of great interest for all coastal-engineering projects.

VII. TEST SITES AND TIMES OF OBSERVATION

A. POTENTIAL TEST SITES FOR STUDY OF OCEAN RESOURCES

An aircraft test program designed to acquire data addressing the identified management issues of the chapter on the biology of the ocean can be constructed in a limited geographical area. It is suggested that such a test program be mounted along the coastal zone of the Pacific Northwest states. This region is indicated for several reasons; particularly, since all of the identified issues can be localized in this one area. In the following paragraphs each of the issues and their particular occurrence in the Northwest will be documented.

The Pacific Northwest coastal zone is one of the more productive fishery regions of the United States, and it encompasses both surface and deep water fisheries. In the summer months, many of the surface fisheries are influenced by the seasonal upwelling which occurs sporadically along the Northwest coast. Thus, this area is a prime candidate for verification of those instruments which can provide both dynamic data related to upwelling and verification of upwelling events. In addition, the Northwest has had recurrent problems with incursions from foreign fishing fleets; thus, any surveillance system could adequately be tested against the domestic and foreign fishing fleets operating within the coastal zone of the Pacific Northwest states. This area also has extensive estuarine fisheries of both sport and commercial interests.

The estuarine areas of the Pacific Northwest are varied and contain both marshland and broad tidal flats. Thus, the imaging systems in a proposed surveillance aircraft could be utilized to monitor both the vigor and extent of coastal marshes, and the extent and potential productivity of the tidal flatland areas. The differing nature of the estuaries along the Northwest coast provides an environment for testing 1) the various sensor systems as they pertain to determination of typical circulation patterns, and 2) the utility of the systems for demonstrating control of periodic unplanned events, such as oil spills or other incursions into the normal regime of the estuary.

The estuaries and coastal zone of the Pacific Northwest are also visited by such migratory species as the gray whale, small dolphins, and waterfowl of various sizes and descriptions. Thus, this area also lends itself to the testing of imaging systems as a means of taking inventory and tracking the movements of migratory species of interest in the coastal zone.

Other areas within the United States coastal zone could also be suggested as potential test sites. Perhaps the second choice would be an area of the Middle Atlantic states containing large estuaries, large marshland areas, and the broad continental shelf with its fisheries. For purposes of a test program, however, it is felt that the Northwest demonstrates all aspects in a much more concisely placed fashion, and also it has within a smaller geographic area a large variability, thus adding to its desirability.

B. POTENTIAL TEST SITES FOR EROSION STUDY

The quality of a test site for study of coastal erosion is characterized by a good exposure to ocean waves coming from a given direction, a geologic formation which is fairly well known, and possible ground access to the site to check the results. The following test sites, on the California coast, have been chosen. The first proposed test site is Point Mugu, California, which is exposed to westerly waves and, to a lesser degree, to southwesterly wave trains. This test site is already surveyed at regular intervals by the U.S. Army Corps of Engineers, who study the beach profile variations.

The second test site is the area between San Clemente and Carlsbad, California. This straight coast receives west to south swells during the summer and autumn periods. Its bluffs and sand beaches are convenient for monitoring variations.

The third site which is proposed is the area of Monterey Bay, California, in San Mateo County. This area is exposed to northwest and west swells which occur during the winter and spring seasons. The area was chosen for the different geological structures of the coast. Stripes of hard rock extend up to the coast alternating with softer materials. Access is possible for ground check of these sites.

C. POTENTIAL TEST SITES FOR COASTAL ENGINEERING STUDY

The choice of these sites has been made mainly to study wave patterns. The different locations may already have been partly studied or some ground measurement equipment may already exist. These sites are located on the east coast; i.e., the New York bight, the east coast of Florida, the Carolina bight, and on the west coast the Santa Barbara channel up to Point Conception. The times of the year most suitable for flights depend on the type of data desired and on the location of the site. The Santa Barbara channel usually has high waves from west-northwest in March. It yields good refraction diagrams and good wave information up to Point Mugu, while the eastern coast of Florida can be a site of interest during the whole year, if the results are to be composed to the wave climate model developed by the U.S. Army Corps of Engineers. The East Coast flights are especially interesting in November, when large waves are generated in the Atlantic and arrive at the coast under reasonably good optical visibility, and in March, when limited fetch experiments can be conducted in areas where the wind is blowing from the coast toward the sea. These sites should yield interesting results on wave climates for relatively large areas of the ocean.

VIII. FLIGHT PLANS

Figures 17 and 18 show the areas proposed as test sites and patterns which could be used during the flights. On the West Coast (Fig. 17) several areas are marked which can be flown over in one or several missions. It is assumed that the plane is based at Moffett Field, near San Francisco, California. The Santa Barbara channel is expected to be surveyed with a flight path which is adapted to the ground truth equipment available. The portion of the flight which is not indicated can be used for experiments to be flown over land or for observation of storms and swells in deep water further from the coast.

Figure 18 shows the East Coast where three main testing areas have been chosen. These areas must be flown over according to a pattern determined by the ground truth requirements. The start and end of the flight(s) will depend on the place where the airplane is based.

IX. CONCLUSIONS

We have proposed in this report a series of experiments and test flights to obtain data on the coastal zone and to learn to use these data. The reasons this kind of information is needed and the advantages it presents have been shown. After the experimental part of the program, i.e., after the best technique for coastal observation has been defined and tested, an operational program will have to be established.

Such a coastal observation program will definitely be of interest to the community at all levels, for fisheries or for coast protection, and for coastal-engineering works or for any other coastal improvement. The program should consist of observations on a regular schedule, from a satellite or from a plane, depending on the scale of the phenomenon studied and on the type of sensor used. The remote sensor, associated with or without another sensor, should be determined by the type of information wanted, i.e., wave pattern, water temperature, coast erosion, etc. Several different sensors can be used at the same time during a multipurpose mission where several physical and biological parameters are needed. We have seen that for each civil engineering project, a large amount of data is required. A coastal observation program would lead to a substantial savings in dollars for such a project, since the cost of such missions would be less than the cost of obtaining the necessary data by conventional means. The cost could be further reduced if the flight program was incorporated in or associated with other experimental studies over the ocean and its coastal region.

The information received on a regular schedule could be gathered by one of the existing government agencies and later provided for private users, according to a procedure yet to be defined. In parallel, a coastal-observation program would improve the scientific knowledge of the coastal region.

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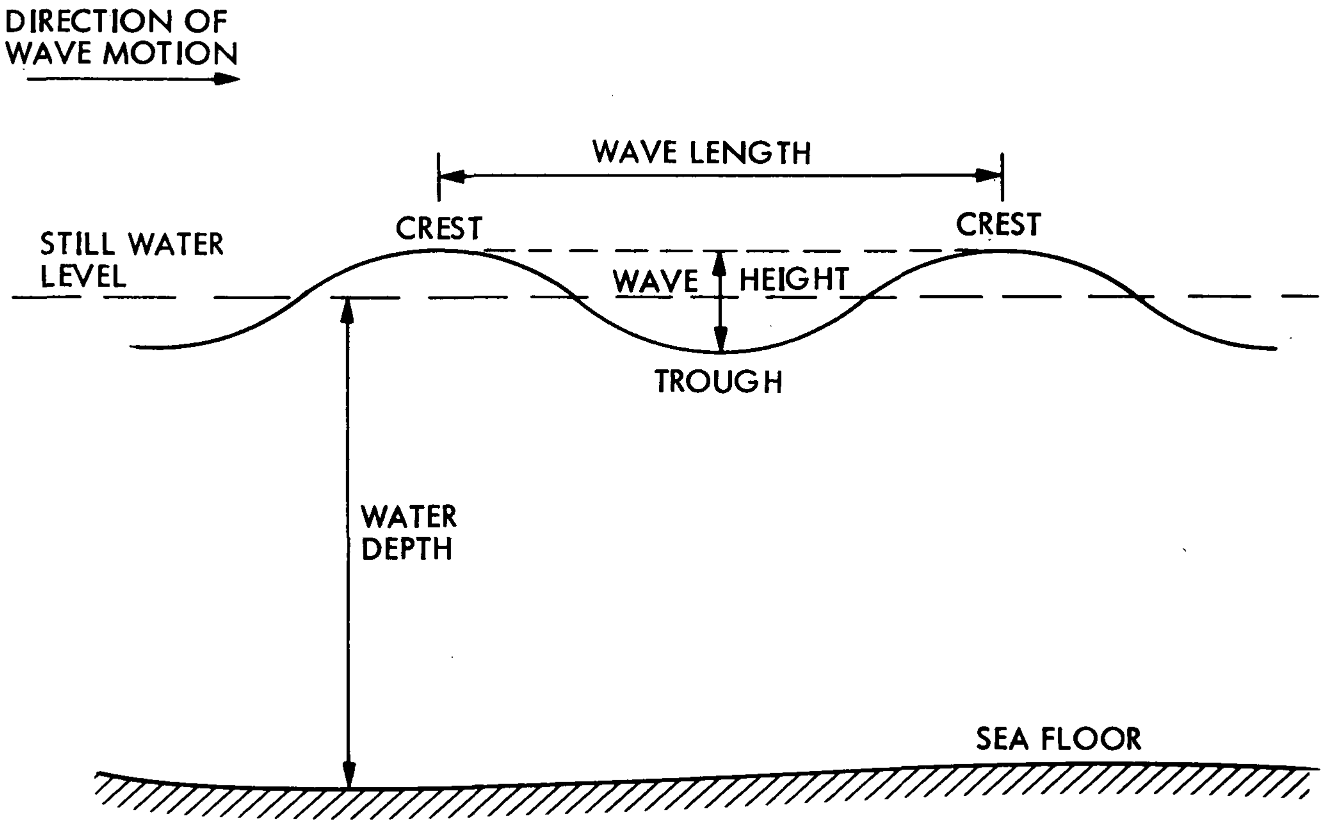

Figure 1. Characteristics of an ocean wave

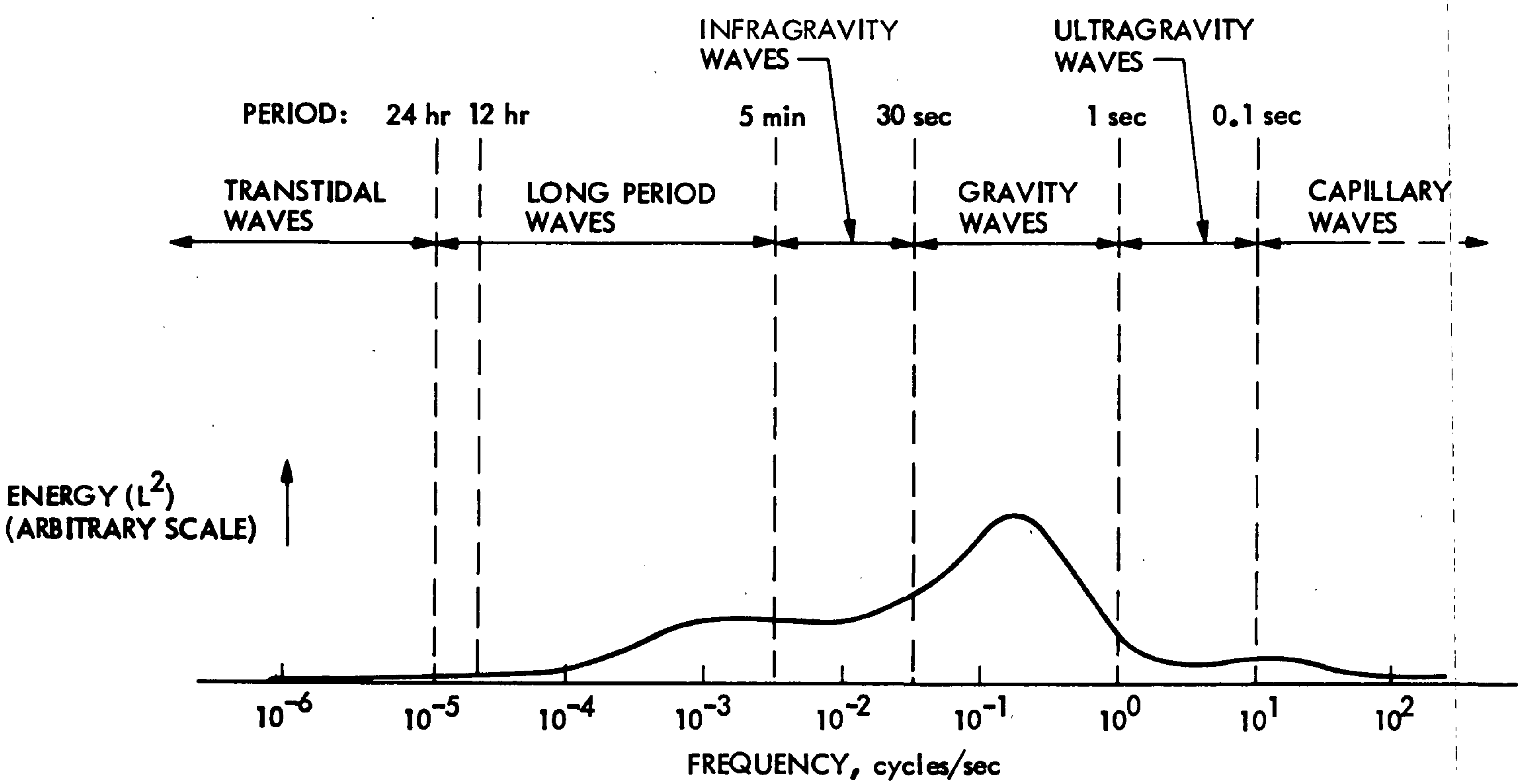

Figure 2. Arbitrary representation of the energy contained in ocean waves

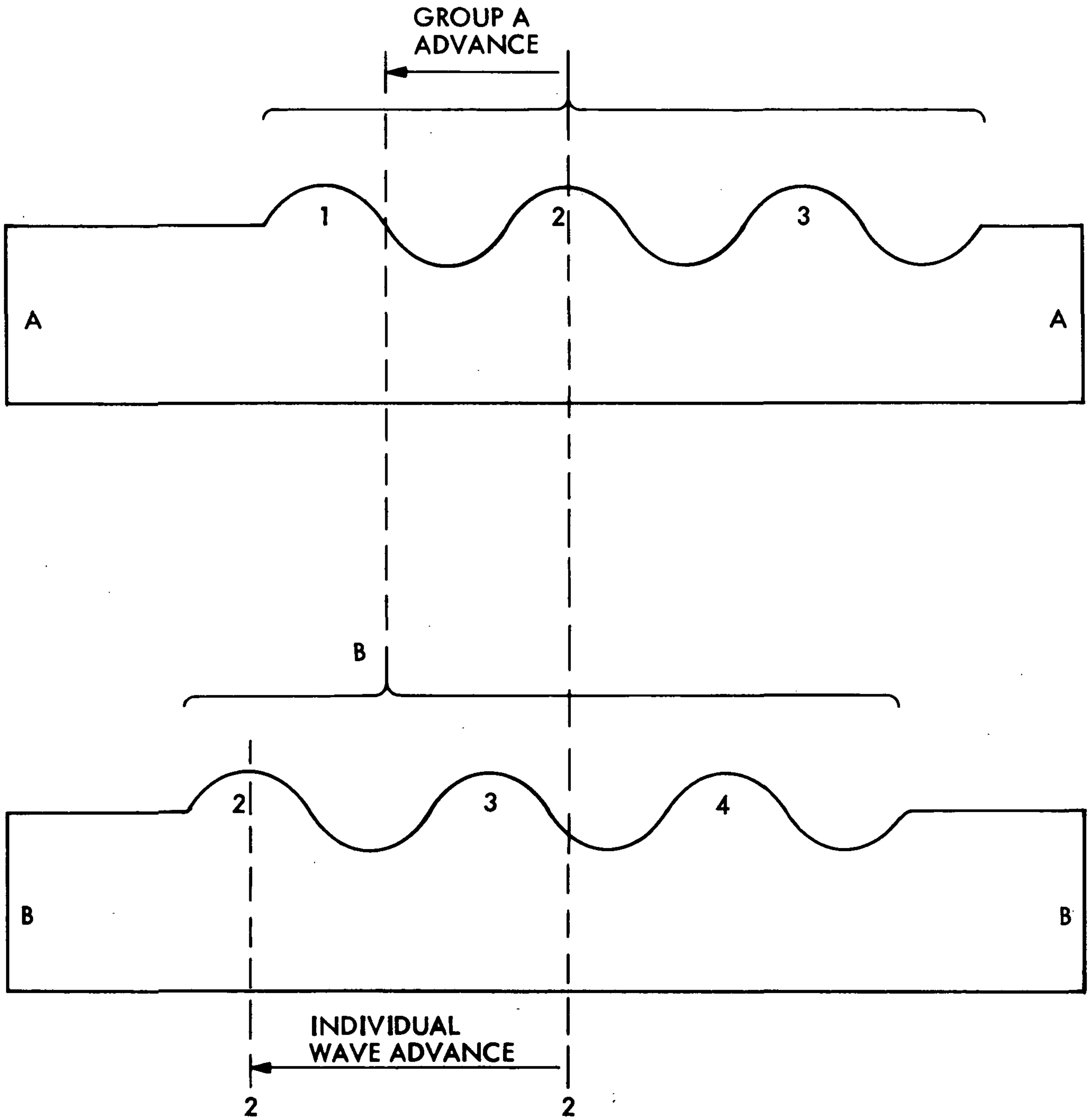

Figure 3. Wave group advance

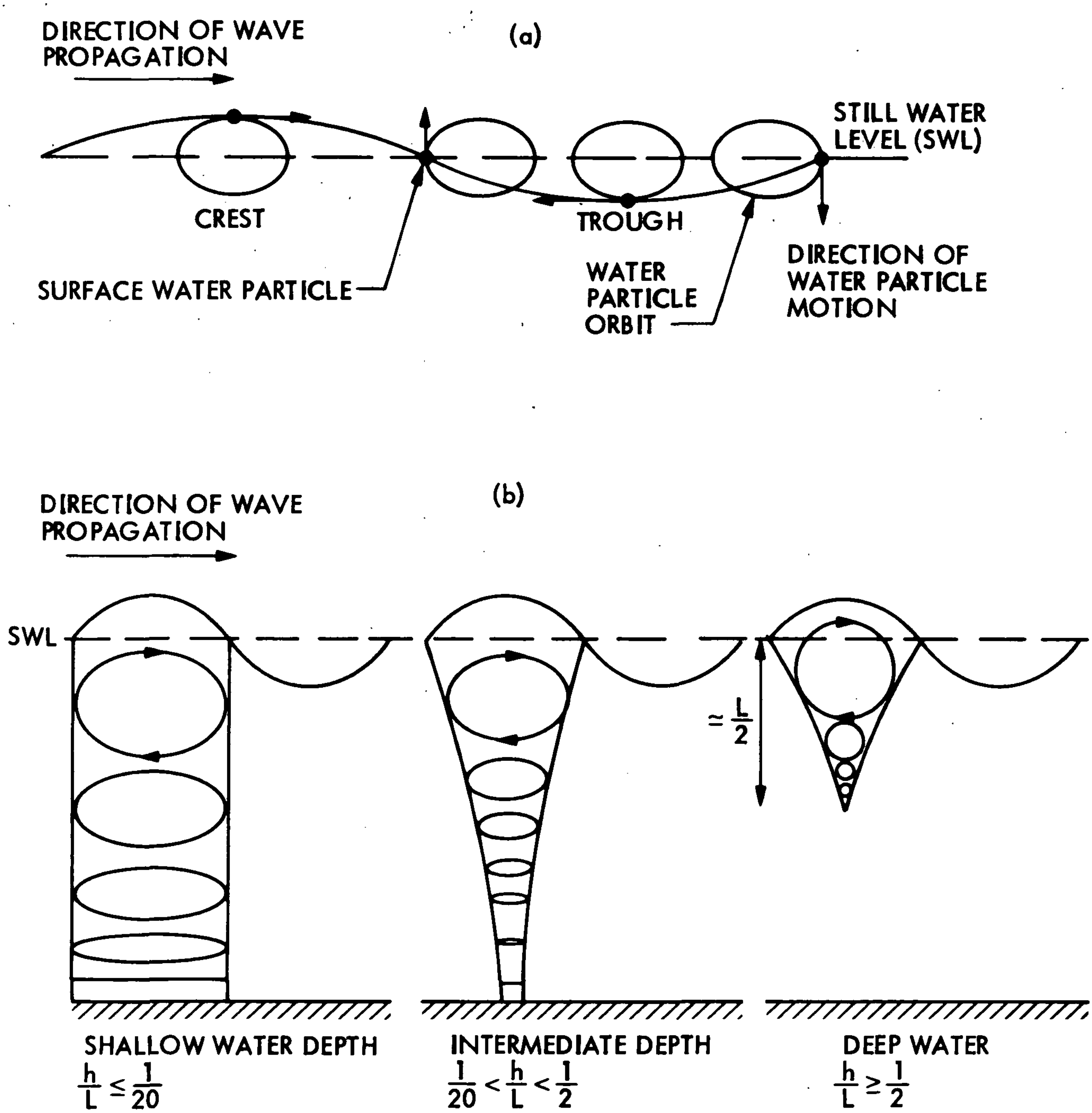

Figure 4. Orbital motions of water particles in waves

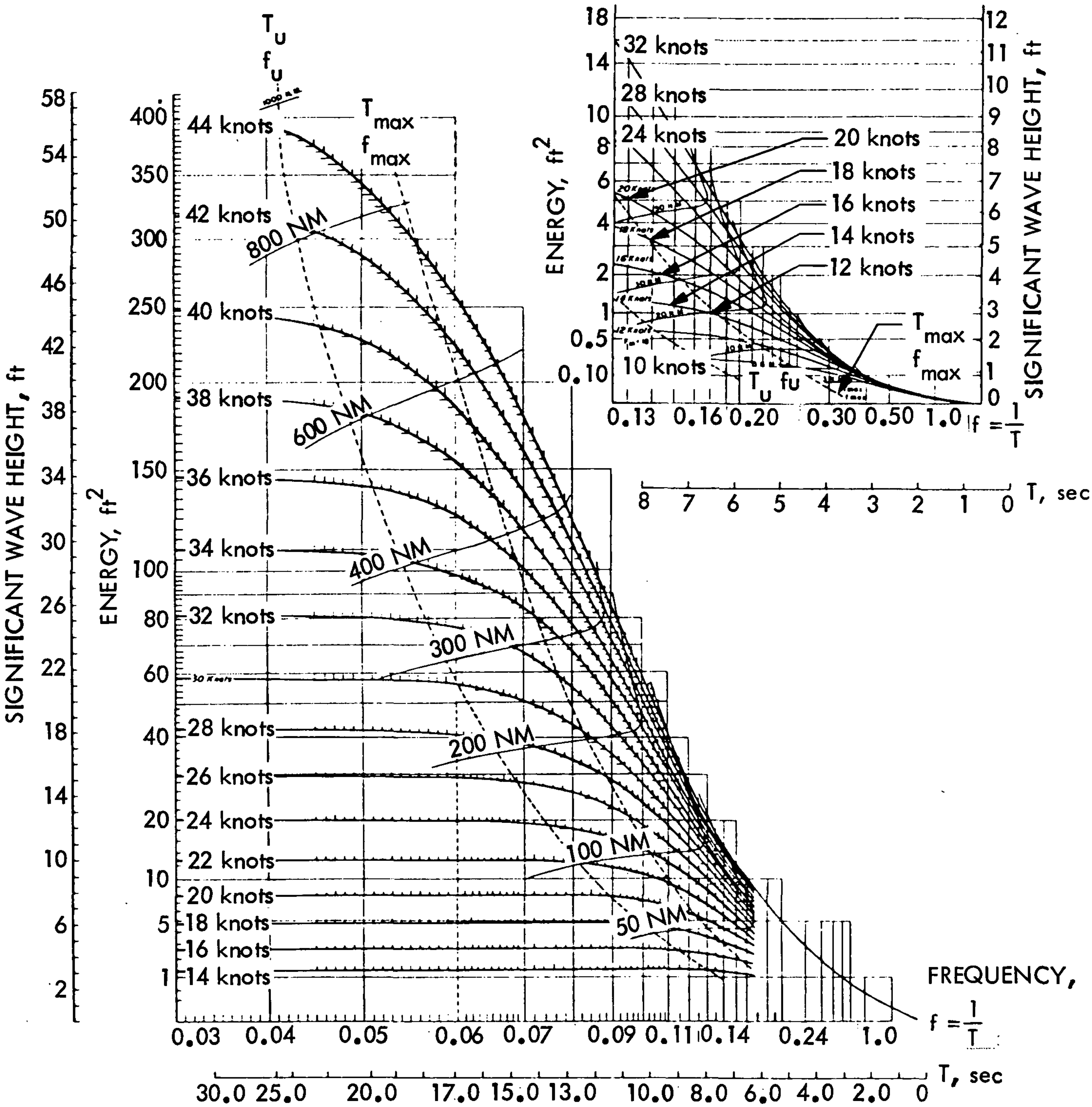

Figure 5. Fetch graph: distorted co-cumulative spectra for wind speeds from 10 to 44 knots as a function of the fetch (after Pierson, Neumann, James, ref. 2)

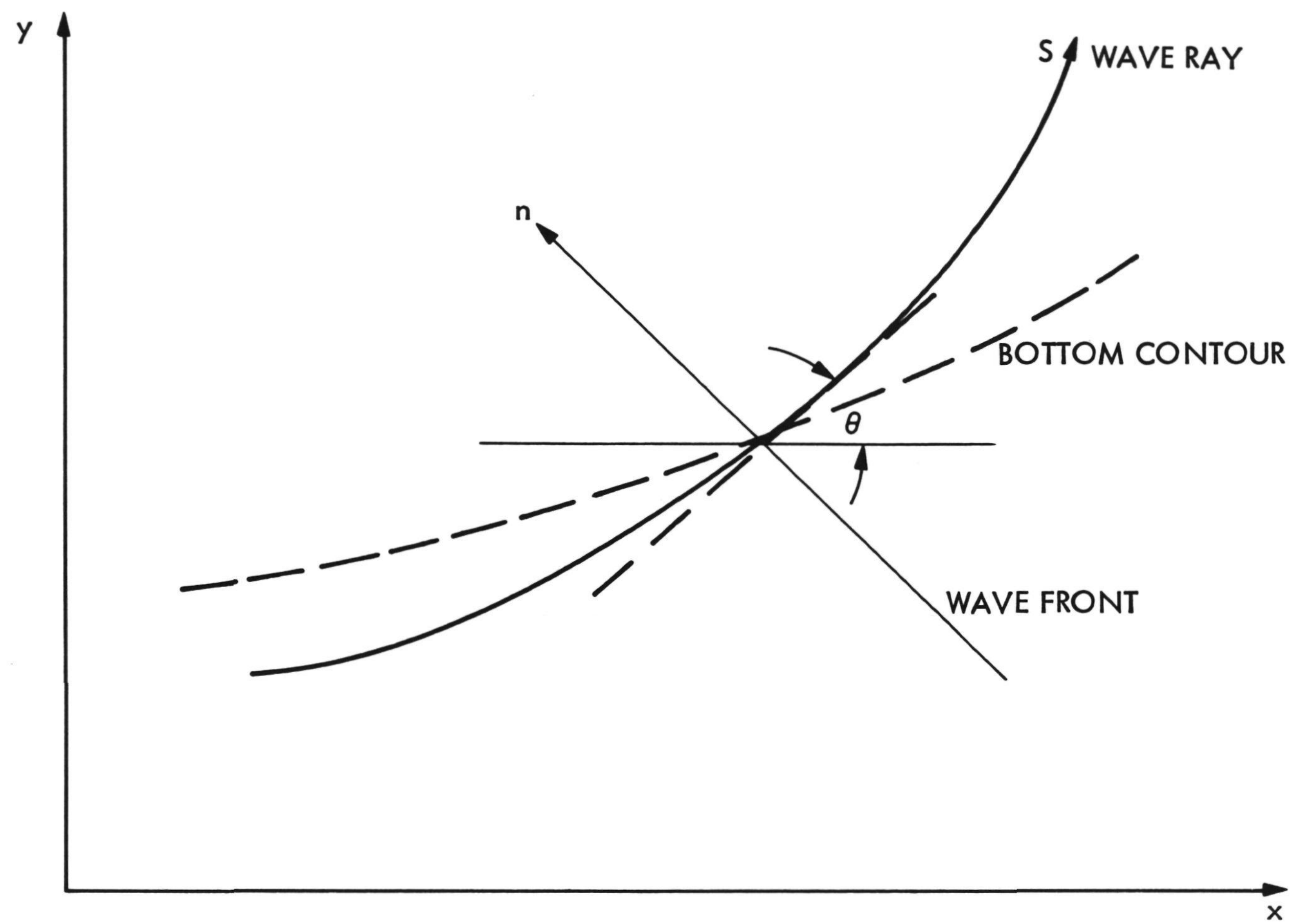

Figure 6. Construction of refraction diagrams by the direct-ray method

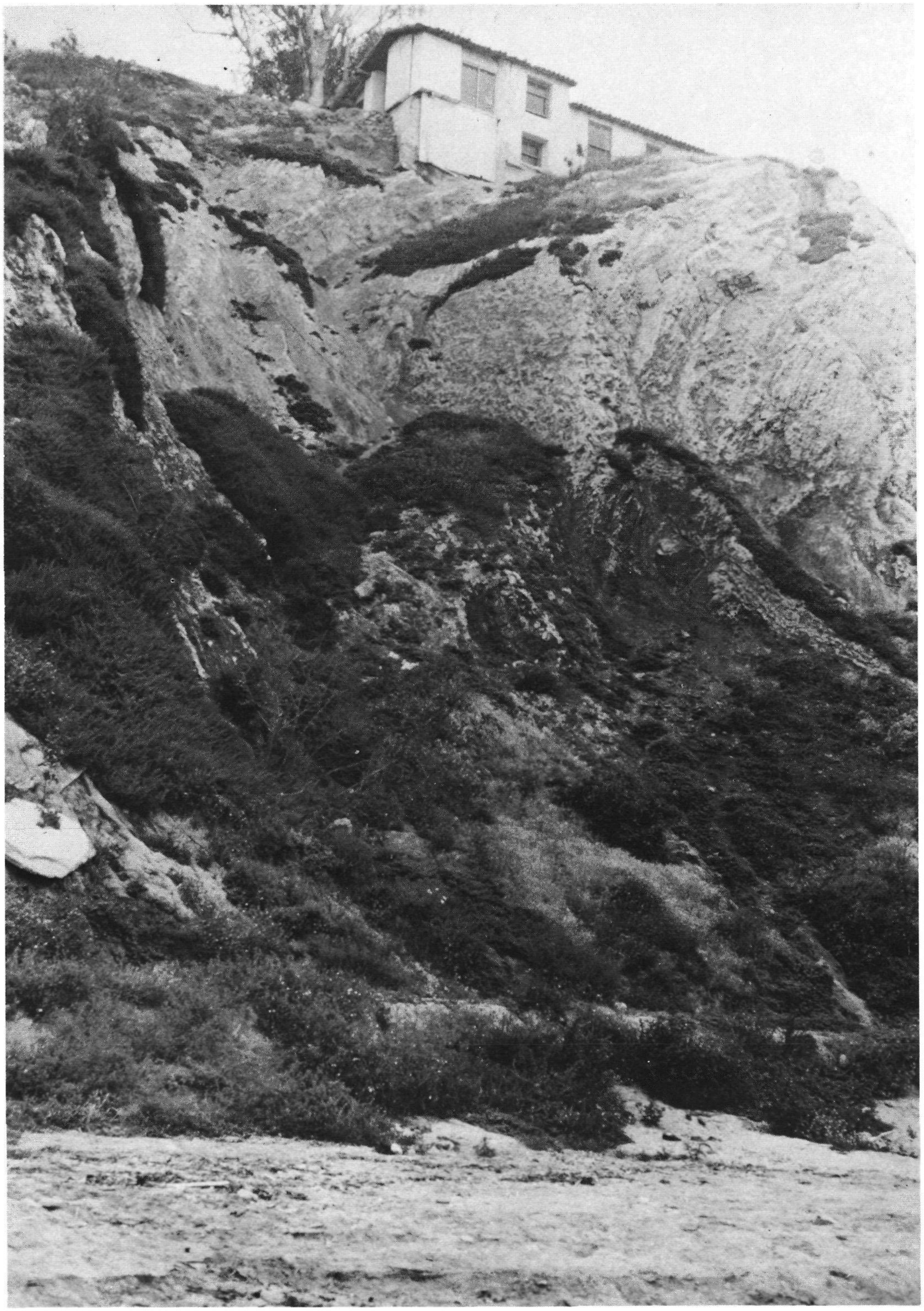

Figure 7. Coastal erosion:
bluff erosion endangering a house
(Maliga Cove, California)

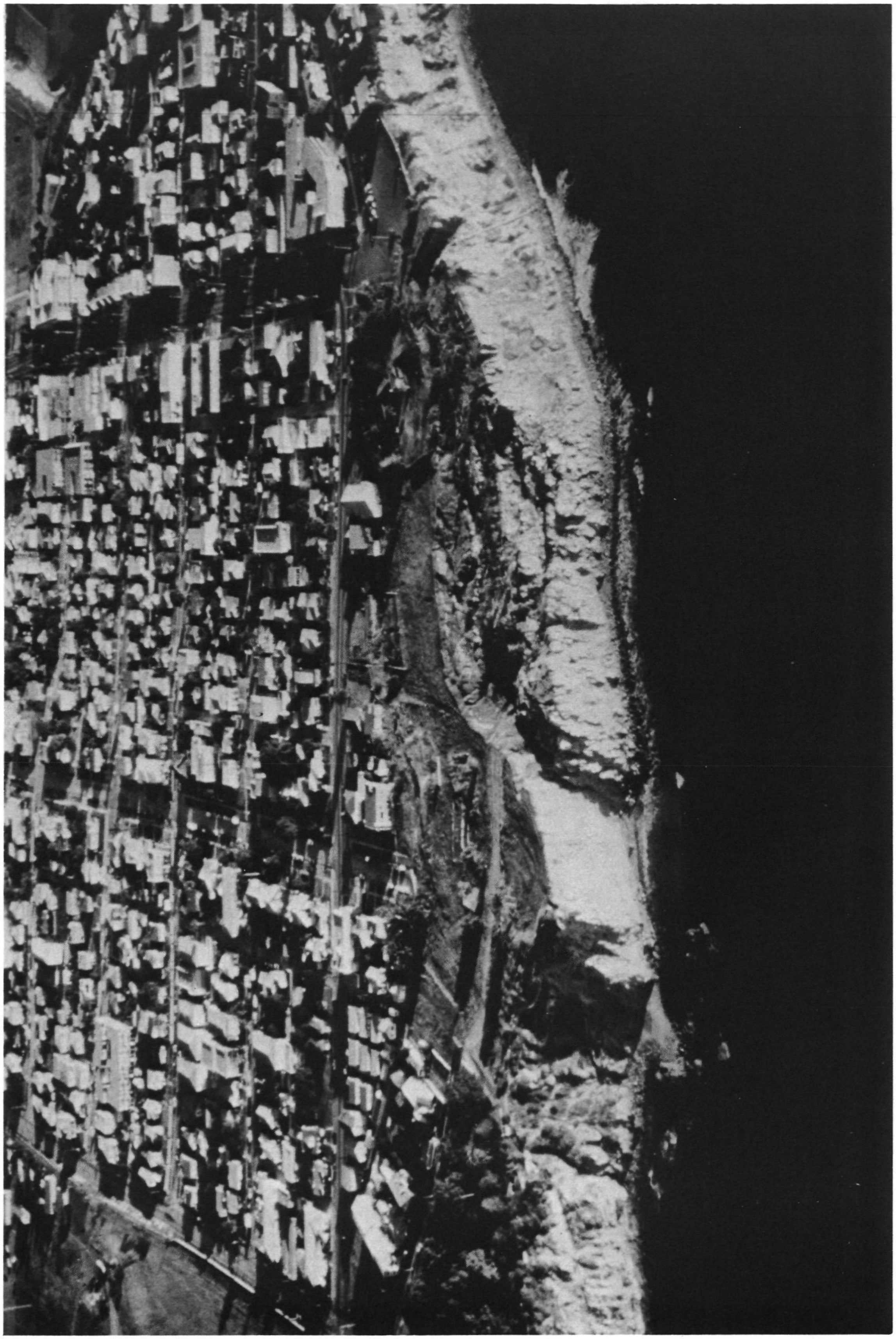

Figure 8. Coastal erosion: bluff regression (Point Fermin, San Pedro, California)

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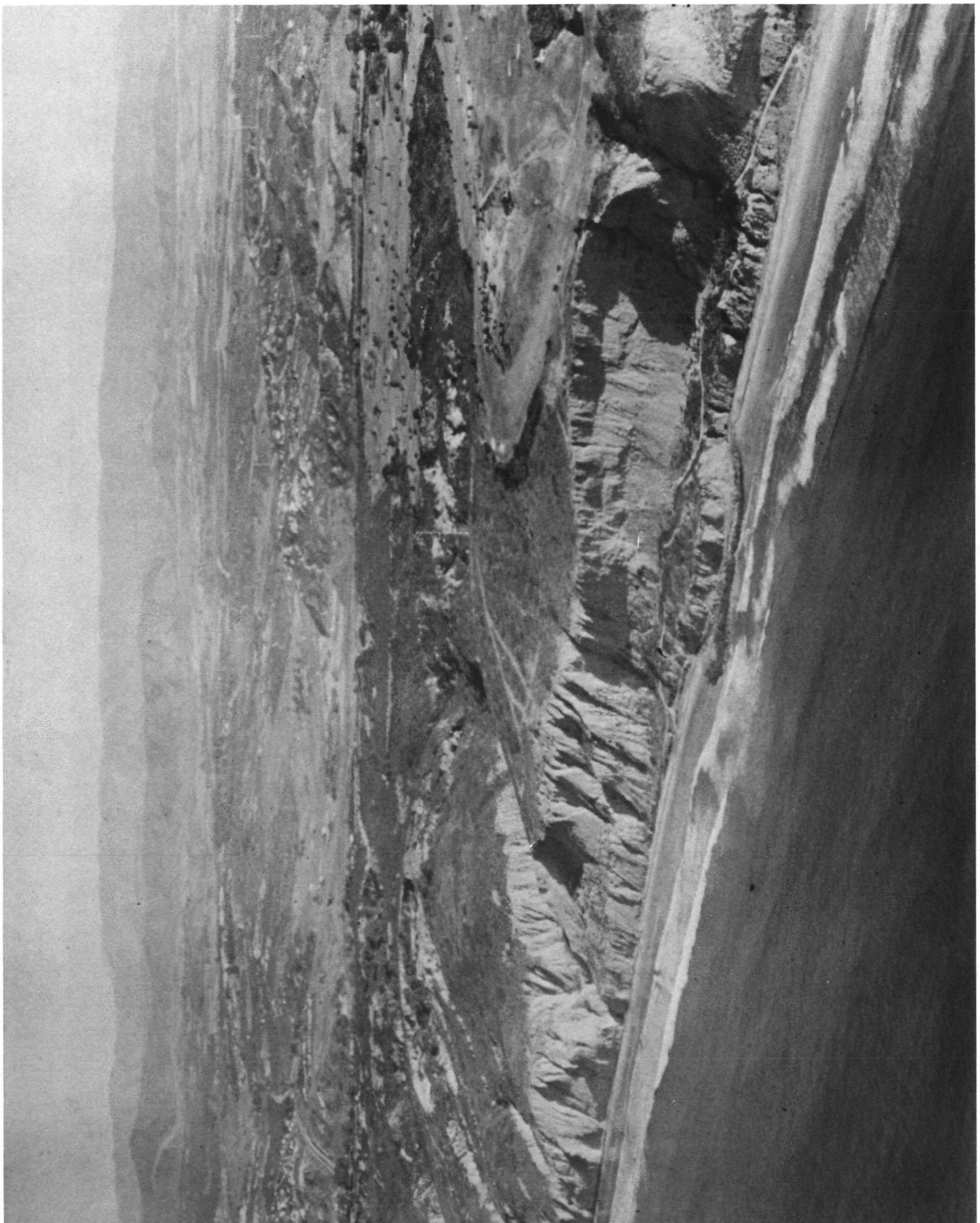


Figure 9. Coastal erosion: Del Mar to La Jolla, California

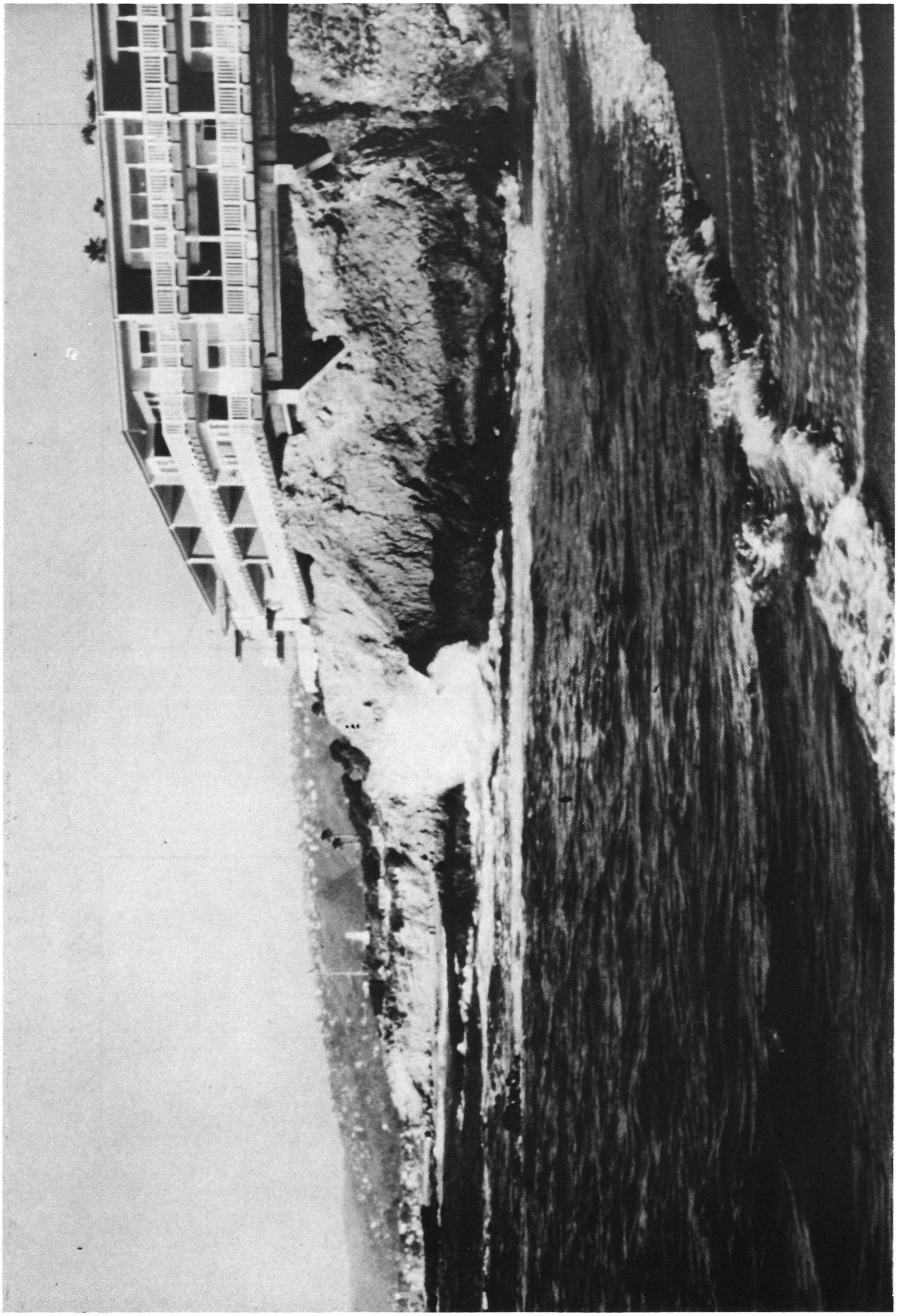


Figure 10. Coastal erosion: endangered construction

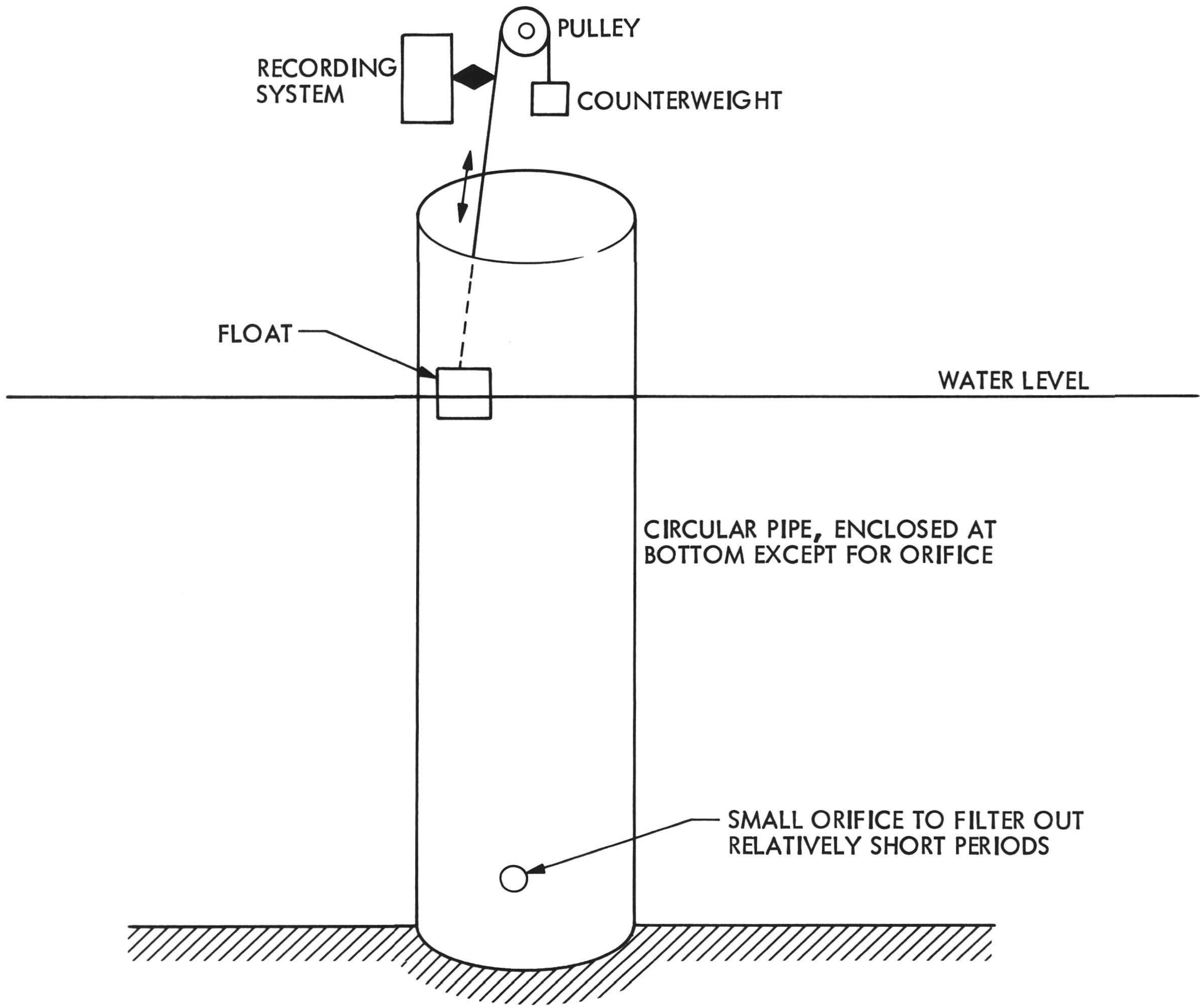


Figure 11. Tide-recording apparatus

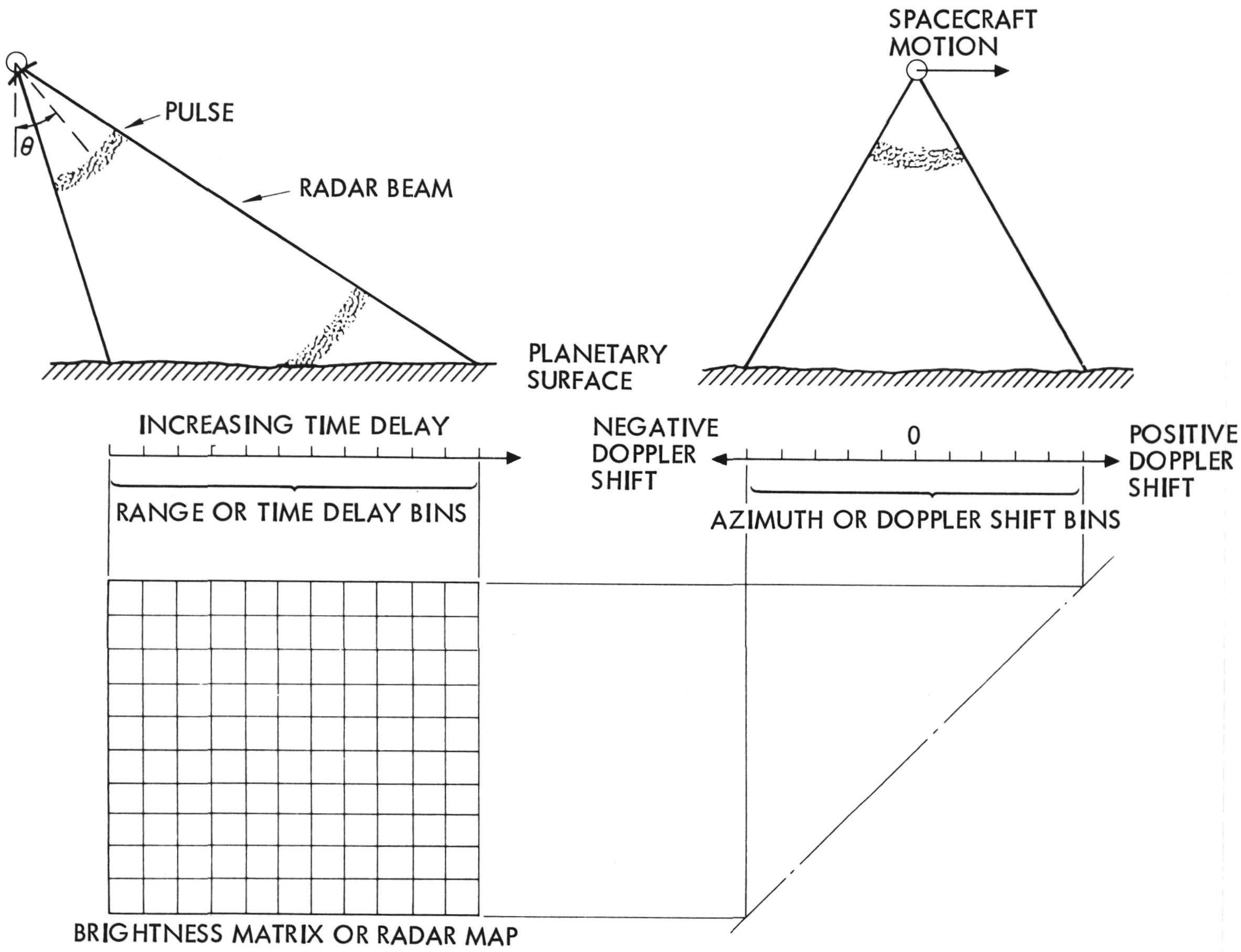
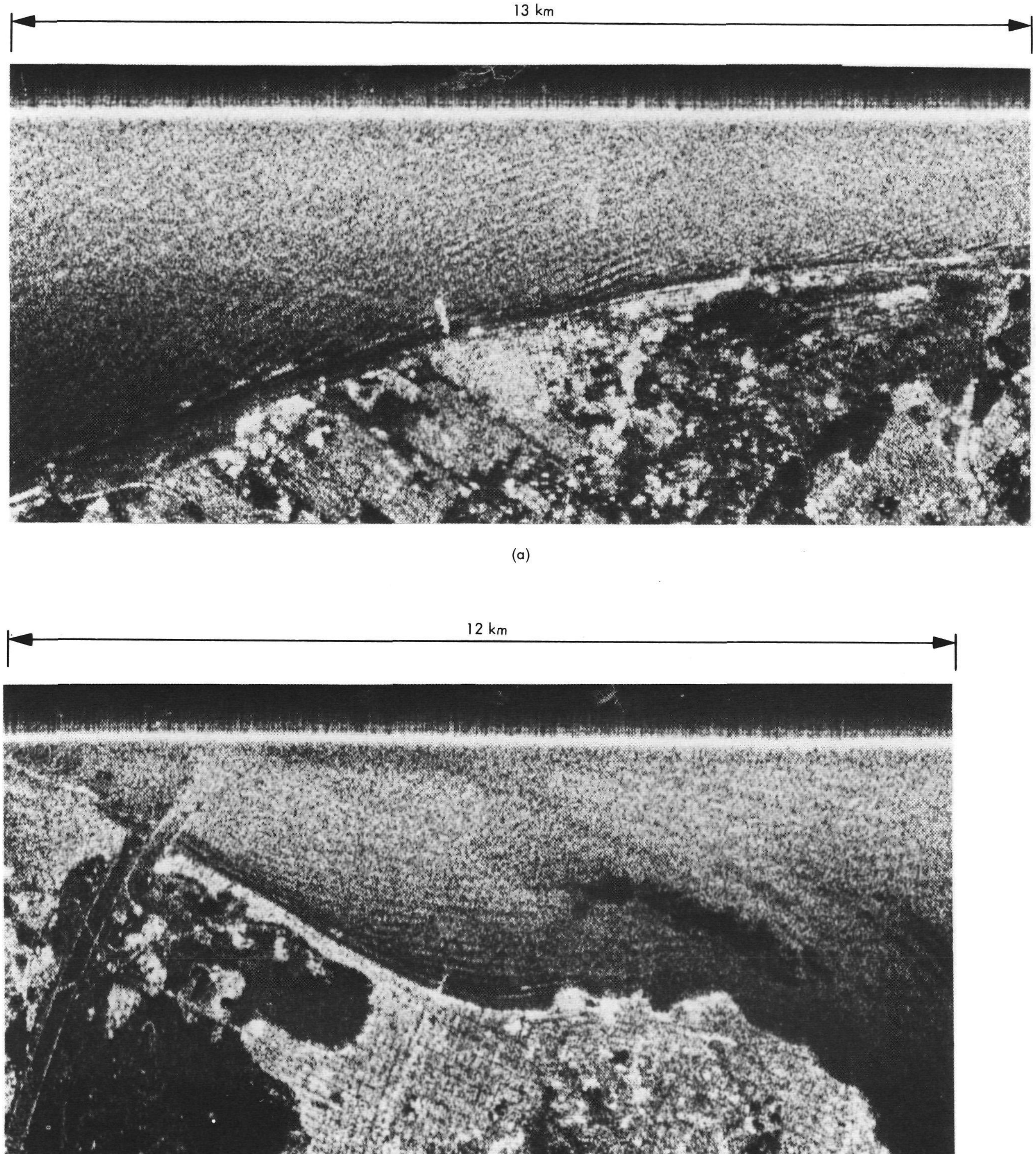


Figure 12. Coherent imaging-radar principle: 1) range resolution is obtained from the time-delay information; 2) azimuth resolution is obtained from the Doppler information; 3) simultaneous time-delay and Doppler processing provides a two-dimensional brightness map



(b)

Figure 13. Example of radar imagery:
(a) Huntington Beach, California,
(b) San Diego, California

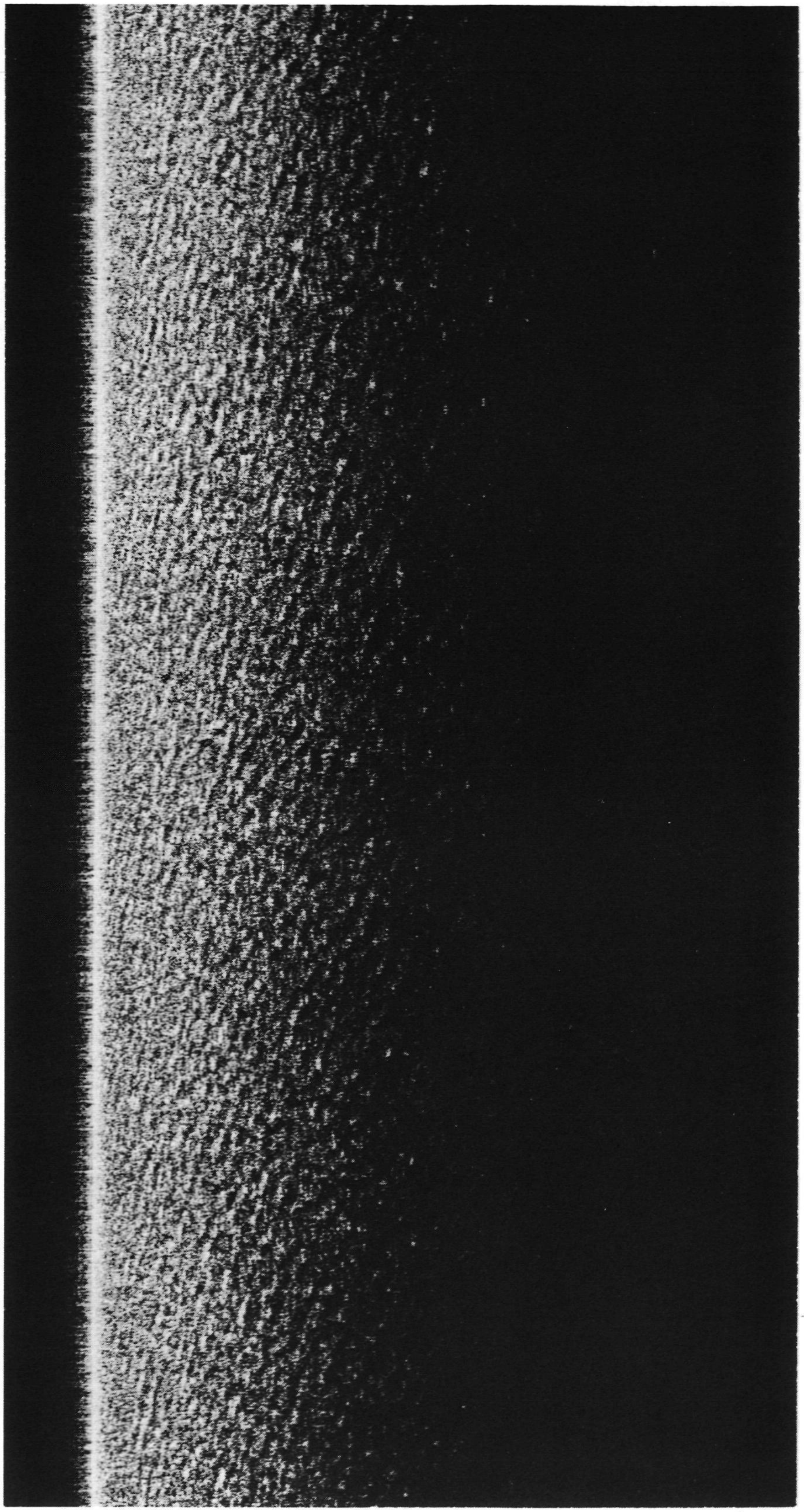


Figure 14. Example of radar imagery: ocean waves in the North Atlantic ocean

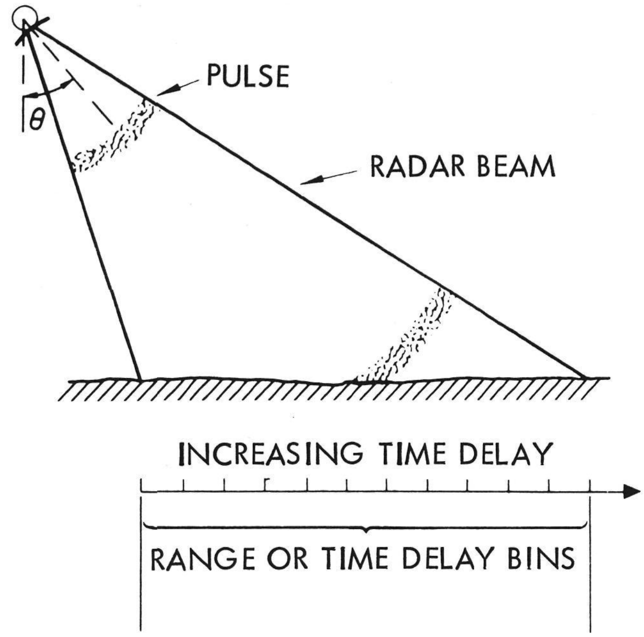


Figure 15. Side looking scatterometry

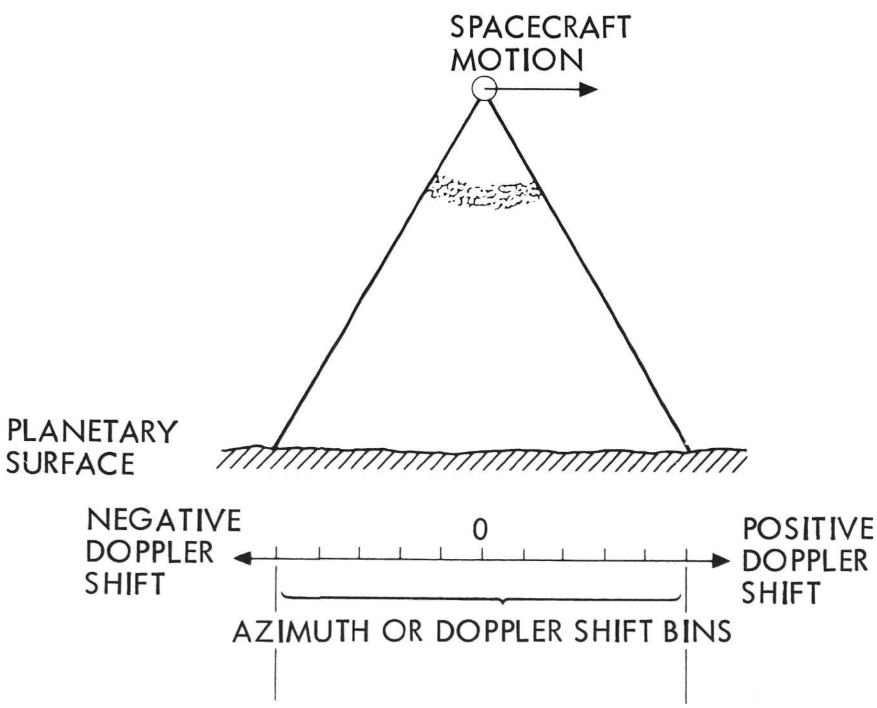


Figure 16. Doppler scatterometry

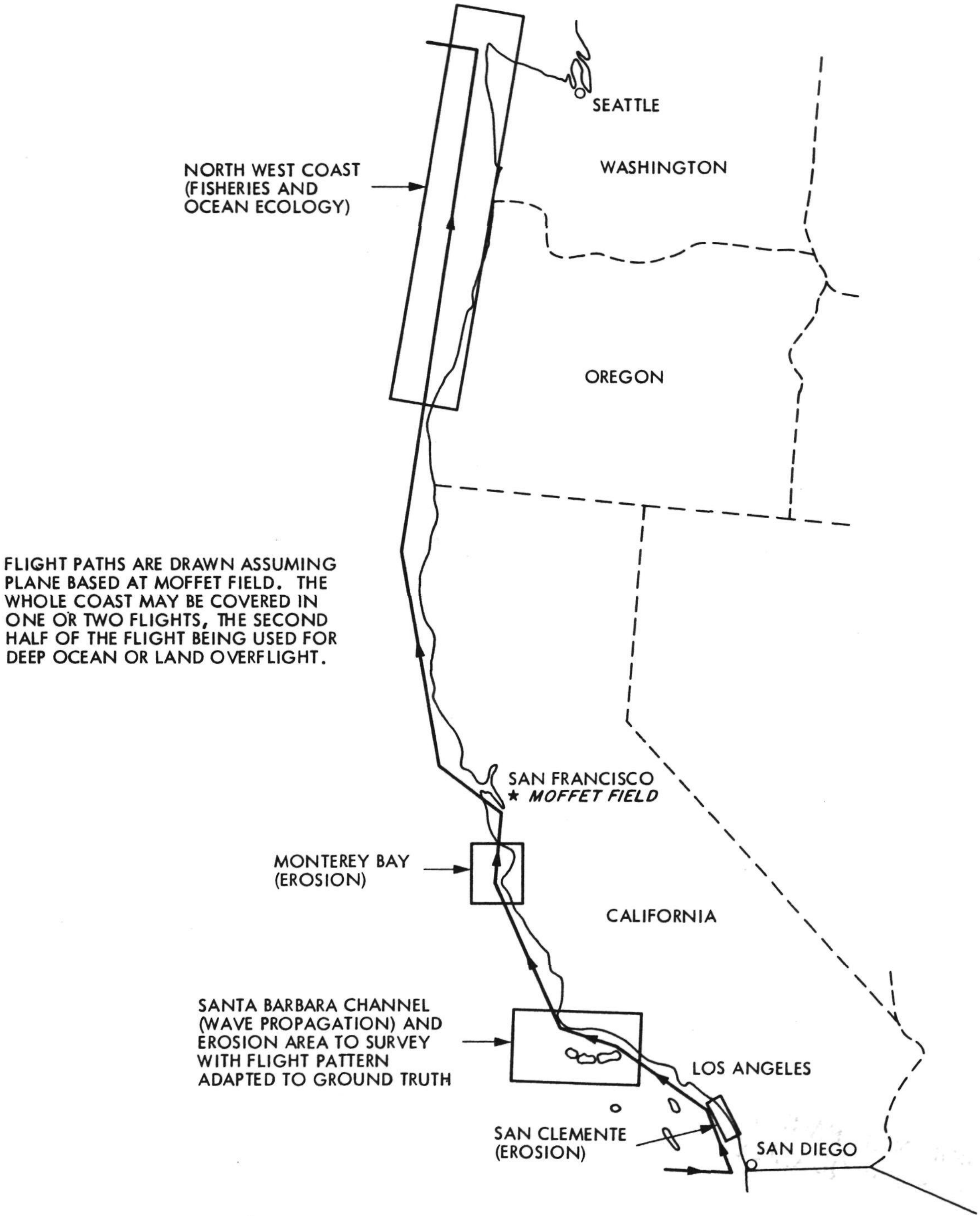


Figure 17. Test sites and flight paths on the West Coast

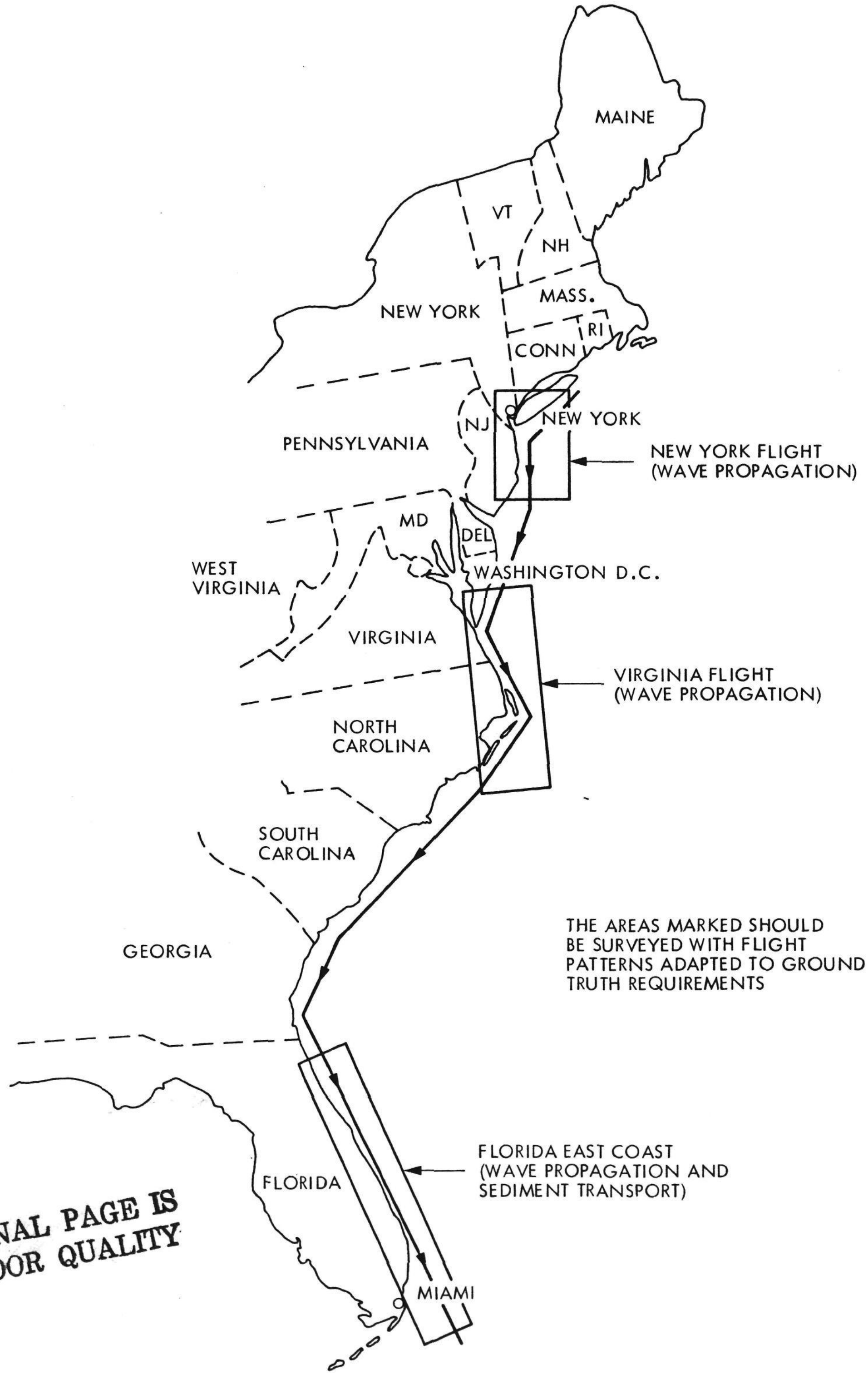


Figure 18. Test sites and flight paths on the East Coast

NASA — JPL — Coml., L.A., Calif.